Yield Models for use in DSM Localised Loading Design of Hat Sections

Zhehang Chen1, Cao Hung Pham2, Gregory J. Hancock3

Abstract

The direct strength method (DSM) of design is a newly developed method for the design of cold-formed steel members. It has been well developed and incorporated into the North American Specification AISI S100 and the Australian/New Zealand Standard AS/NZS 4600 for cold-formed steel sections under compression, bending and shear. Recently, a consistent and simplified DSM for the design of cold-formed steel structural members under localized loading has been developed for single web sections such as channels and zeds and was published in the literature. However, there are no methods available for multiple web sections such as hat sections and decking. The mechanical behaviour of multiple web sections is not yet fully understood and there have been to date few publications, discussing the mechanical behaviour of hat sections under localised loading. This paper proposes and explains a yield model in determining the yield load (P_y) for use in the DSM for localized loading design of hat sections. It has to be taken in conjunction with the elastic buckling load P_{cr} described separately. A series of equations is developed to calculate P_y for both vertical-web and sloping-web sections. A detailed discussion on the different models of the yield load (P_y) is also included.

1. Introduction

The history of studies on web crippling of cold-formed steel structural members dates back to early 1940s. Due to the complexity of the theoretical and analytical analysis, most of the formulae have been developed based on empirical data and a curve fitting method. Bakker and Peköz [1] have pointed out the fact that most of the curve fitting formulae fit the test results on which it is based, but they have poor correlation with other formulae based on similar research. In recent years this problem has been partially solved by a newly developed design method called the Direct Strength Method, which has been well developed and incorporated into the North American Specification AISI S100 [2] and the Australian/New Zealand Standard AS/NZS 4600 [3] for cold-formed steel sections under compression, bending and shear. Recently, a consistent and simplified DSM for the design of cold-formed steel structural members under localized loading has been developed for single web sections such as channels and zeds and was published by Nguyen et al. [4]. However, there are no methods to date available for multiple web sections, such as hat and decking sections.

The primary objective of this research is not to solve the entire problem for multiple web sections but to provide a simple and consistent method for calculating the P_y values for use in the DSM for localized loading design of hat sections. In this paper, only two-flange loading cases are considered. In order to be consistent with the determination of P_y for C sections as given by Nguyen et al. [5] and RHS sections given by Zhao and Hancock [6], a yield model is proposed on the basis of the yield line method. An amendment for covering sloped web sections is also provided.

Two sets of data are used to verify the proposed yield model. The first set of data is collected from the lab testing results conducted by the authors. The second set of data is collected from a report by Wu, Yu and LaBoube [7]. During the verification process, a new form of DSM equation is proposed. Finally, some conclusions and recommendations for further research are summarized.

2. Yield model

2.1 Basic concept of DSM
Generally, the DSM design equations are based on two input variables: an elastic buckling load \( (P_{cr}) \) and a yield load \( (P_y) \). Nowadays the methods for determining elastic buckling loads are well-established. Other than commonly used finite element software ABAQUS developed by Dassault System, there are two widely accepted software packages for calculating elastic buckling loads specifically available for thin-walled sections. The first one is CUFSM developed at Johns Hopkins University and the other, which was specifically developed and designed for the Direct Strength Method and was the only software package that deals with localized loading, is called THIN-WALL-2 developed at the University of Sydney [8].

Regarding the calculation of the yield load, there is no consistent methods among different sections because they have different behaviours under localized loading. However, the fundamental concept for simplification is consistent: a yield line theory is adopted for calculating the yield load, assuming a balance between the internal and external energy. In this paper, a simplified model is proposed for use in the determination of the yield load for use in the DSM equations. Firstly the vertical web section is discussed followed by amendments and adaptations for the sloped web sections.

### 2.2 General yield model for vertical web sections

A general yield mechanism model is created based on the yielding behaviours observed from various FEM simulation models and experimental testings for different section heights. This general yield mechanism model with vertical webs can be used for different load cases provided that different parameters are selected for the length and location of the hinge lines. Figure 1 shows the cross-section view of the general yield mechanism model for two flange loading cases with load locations and possible hinge locations. Sloped web sections are discussed in next section.

The yield mechanism load \( P_y \) is given by

\[
P_y = k_w F_{SW}
\]  

\( k_w \) is the number of webs in the section. For Hat sections, \( k_w = 2 \) and for channels and Z sections, \( k_w = 1 \). \( F_{SW} \) is the load calculated for the yield lines in a single web. For equilibrium using the virtual work principle, the external energy of the load acting on the loading plate must be equal to the internal plastic energy in the hinges. The energy equation for a single web can be therefore written as:

\[
F_{SW} \times (r_c \theta_1 + r_c \theta_2) = M_p \times \sum_{i=1}^n \omega_i L_i
\]

\[
M_p = \frac{f t^2}{4}
\]

where

\( \theta_1 \) is the rotation for the top corner.

\( \theta_2 \) is the rotation of the bottom corner.

\( \omega_i \) is the rotation angle at each plastic hinge.

\( M_p \) is the plastic moment per unit length of plate.

\( L_i \) is the length of each yield line, which is discussed in detail in the next section.

\( r_c \) is the centreline corner radius. \( r_c = r_{in} + 0.5t = r_{ext} - 0.5t \), where \( r_{in} \) is the inside corner radius, \( r_{ext} \) is the external corner radius and \( t \) is the thickness of the section.

Thus \( F_{SW} \) can be rewritten as

\[
F_{SW} = \frac{M_p}{(\theta_1 r_c + \theta_2 r_c)} \times \sum_{i=1}^n \omega_i L_i
\]

For a single web, four plastic hinges are defined with rotation angles as \( \omega_1, \omega_2, \omega_3 \) and \( \omega_4 \) respectively. From the top to the bottom, \( \omega_i \) \((i = 1, 2, 3, 4)\) are calculated as follows:

\[
\omega_1 = \theta_1 \\
\omega_2 = \theta_1 + \phi \\
\omega_3 = \theta_2 + \phi \\
\omega_4 = \theta_2
\]

\( \phi \) is defined as

\[
\phi = \frac{\theta_1 r_c + \theta_2 r_c}{b + d}
\]

Thus, \( F_{SW} \) can be rewritten as

\[
F_{SW} = \frac{M_p}{(\theta_1 r_c + \theta_2 r_c)} \times [(\theta_1 \times L_{TF} + \theta_2 \times L_{BF}) \\
+ (\theta_1 + \phi) \times L_{TW} + (\theta_2 + \phi) \times L_{BW}]
\]

where

\( L_{TF} \) and \( L_{BF} \) are the length of the yield lines in the top and bottom flanges respectively.

\( L_{TW} \) and \( L_{BW} \) are the length of the yield lines in the top and bottom of the web respectively.

In order to simplify the yield mechanism model, for two flange loading cases, the assumptions listed below are based on observations from the FE models.

1) The hinge locations on the webs are symmetrical between the top and bottom so that

\[
a = c, b = d
\]

2) The rotation angle at the top and bottom of the web are identical so that
\[ \theta = \theta_1 = \theta_2 \]  

Consequently,

\[ \omega_1 = \omega_4 = \theta_1 = \theta \]  
\[ \omega_2 = \omega_3 = \theta_1 \times \left(1 + \frac{a}{b}\right) = \theta \left(1 + \frac{a}{b}\right) \]  

Based on Equation (2), the general equation for the capacity of a single web for hat sections under localized loading is:

\[ F_{SW} = \frac{M_p}{k_{\theta} c} \times \sum_{i=1}^{n} k_{\omega_i} L_i \]  

where

\( k_\theta \) is a factor for the number of loaded flanges, for two-flange loading cases, \( k_\theta = 2 \), and \( k_{\omega_i} \) is a factor for the rotation angle at each plastic hinge. Based on Equations (11) to (14), Equation (15) can be rewritten as

\[ F_{SW} = \frac{M_p}{2k_{\theta} c} \times \left[ \theta \times L_{TF} + \theta \times L_{BF} \right] + \theta \times \left(1 + \frac{a}{b}\right) \times L_{TW} + \theta \times \left(1 + \frac{a}{b}\right) \times L_{BW} \]  

Since \( \theta \) is not equal to 0, it can be eliminated from both sides of the equation. Thus, Equation (16) can be rewritten as

\[ F_{SW} = \frac{M_p}{2k_{\theta} c} \times \left[ L_{TF} + L_{BF} \right] + \left(1 + \frac{a}{b}\right) \times L_{TW} + \left(1 + \frac{a}{b}\right) \times L_{BW} \]  

The lengths of the yield lines are discussed in the next session.

2.3 Length of yield line

Numerical FEM model and testing results have been used for the determination of the yield line lengths \( L_{TF}, L_{BF}, L_{TW} \) and \( L_{BW} \). The methodology for yield line length prediction is similar to the method proposed for tubular sections by Zhao and Hancock [6], which has been included in the Australian Standards AS4100 [9]. According to the assumptions in previous sections, the location of the yield lines on the top and bottom of the webs are assumed to be symmetric about the half-height of the web and the length of the yield line is assumed to be identical between the top and the bottom. Thus, only \( L_{TF} \) and \( L_{TW} \) need to be calculated.

The lengths of the yield line on the top of flange (\( L_{TF} \)) and top of the web (\( L_{TW} \)) are calculated according to Equations (18) to (20):

\[ L_{TF} = L_w + 2t \]  
\[ L_{CT} = L_{TF} + 2 \times k_{dc} \times r_c \]  
\[ L_{TW} = L_{CT} + 2 \times k_{dW} \times (a - r_c) \]  

where

\( L_w \) is the bearing length of the bearing plate. \( L_{CT} \) is the length at the intersection between the top corner and the web. \( k_{dc} = \frac{1}{\tan \gamma_c} \), as shown in Figure 2. \( k_{dW} = \frac{1}{\tan \gamma_2} \) as shown in Figure 2.

For different loading cases, the values of \( a/H, k_{dc} \) and \( k_{dW} \) are subject to change. These selected values are discussed in next sections. \( a/H \) is defined as the height ratio \( k_H \).

2.4 Summary of the exponents and factors for the plastic mechanism model

Table 1 shows a summary of the exponents and factors for the plastic mechanism models in the ITF and ETF load cases. Once all the exponents and factors are known, the yield load \( P_y \) can be calculated using the equations developed above.

2.5 Summary of the exponents and factors for the plastic mechanism model

An experiment by Zhao and Hancock [10] showed that the plastic-moment capacity of a yield line under axial force needs to be reduced. The reduced plastic moment capacity \( M'_p \) of a yield line is employed on the basis of the previous research conducted by Zhao and Hancock [10] as given by Equation (21). For simplicity, the yield line is assumed to be parallel to the flanges.

\[ M'_p = f_y \frac{L_s}{4} \left[ 1 - \left( \frac{P}{f_y L_s} \right)^2 \right] \]  

where

\( L_s \) is the length of the yield line. \( f_y \) is the yield stress of the material. It should be noted that an iterative method is required since \( P \) is a function of the value of \( P_y \) being calculated. Normally two iterations are sufficient.

2.6 Amendment for sloped web sections

An amendment is necessary to allow for the sloped web of sections with sloping webs. The eccentricity of the load from the loading location to the rotation centre is different from that for vertical sections.
Figure 3 shows the corner details of sloped web sections. Point O is assumed to be the rotation centre of the corner when vertical load is applied to point A. Thus, we have:

$$\beta = \frac{180^\circ - (90^\circ + \alpha)}{2} = \frac{90^\circ - \alpha}{2}$$  \hspace{1cm} (22)

$$e_{cc} = OA = OB = r_c \tan \beta$$  \hspace{1cm} (23)

$$OA = OA' \approx OA''$$, $$OB = OB'$$, $$OD = OD' \approx OD''$$  \hspace{1cm} (24)

$$BD = OD - OB = a - r_c \tan \beta$$  \hspace{1cm} (25)

$$F_{SW} \times (r_c \tan \beta \cdot \beta_1 + r_c \tan \beta \cdot \beta_2) = M_p \times \sum_{i=1}^{n} \omega_i L_i$$  \hspace{1cm} (26)

$$F_{SW} = \frac{M_p}{k_\rho r_c \tan \beta} \times \sum_{i=1}^{n} k_\omega_i L_i$$  \hspace{1cm} (27)

3. Experimental research data

For the confirmation of yield load models, experiments on hat sections were found to be necessary. There have been a few tests on hat sections under localized loading in the literature. The only detailed tests have been conducted by Wu et al. [7] and were limited to slender hat sections with vertical webs yet to be discussed in the paper. In this section, the cross-section details and setups for both tests are discussed. Samples of the test results are collected for further discussion.

3.1 Stocky section tests by Chen

In order to cover the range of hat sections with different thicknesses, especially for the stocky sections, a series of tests has been designed and conducted by the authors. The test setup was designed to perform web crippling phenomenon by controlled deformation in accordance with the Test Standard for Determining the Web Crippling Strength of Cold-Formed Steel Flexural Members, which is also known as AISI S909[11]. Details of the tests is discussed in a draft research report[12] written by the authors.

The setup of the test rig is shown in Figure 10 in Appendix. It should be noted that only two loading cases, ITF and ETF with the bottom flanges fastened, were performed in this test series. There are two reasons for testing the loading case with bottom flanges fastened. Firstly, most of the practical use conditions are likely to put fasteners to hold down the hat section to position. Secondly, in order to keep the original shape of the hat sections, splaying of the sloped web sections needs to be properly controlled. Definition of dimension is shown in Figure 4 where:

- H is the height of the web, measured from the rotational centre.
- W is the width of the top of the hat section, measured from the rotational centre.
- RIN is the inside corner radius for the hat section.
- DEG is the angle between the web and vertical direction, a.k.a. \( \alpha \) in Figure 3.
- LB is the width of the bearing plate.

Since small deformation is expected to occur during the tests, the controlled loading displacement as is set to 10 mm (8.3% of the length of the web, or H as shown in Figure 4) for all the specimens. The load \( P \) from the load cell and displacement \( \Delta \) are recorded during the test. The maximum load \( P_{max} \) is collected as \( P_{exp} \) for use in DSM comparisons in the next section. \( P_{exp} \) is defined as the maximum load capacity within an acceptable range of deformation during a test. Since this research is mainly about the strength not serviceability, the serviceability limit of deformation does not apply. During the tests and FE simulations, it was found that the two post-failure modes identified by Bakker and Stark [13] can be extended to two flange loading. Based on this, there is no peak load when the corner radius is large. Thus, the definition of \( P_{exp} \) is acceptable because large deformation results in significant change of the shape and the load capacity, which requires reconsideration.

3.2 Slender section tests by Wu, Yu and LaBoube

Wu et al. [7] have conducted a series of web crippling tests for hat and decking sections using Grade 80 of A653 steel. Six of those specimens were hat sections and the test setup was similar to tests by the authors. Table 3 shows the dimensions and test results from the Research Report [7]. For simplifications, nominal dimensions are used and the error between the nominal and real measurements is assumed to be negligible.

4. The DSM equations

4.1 General formulae for DSM equation

In order to be consistent with the new form of DSM equations published by Glauz and Schafer [14], a general form of the DSM equations for localized loading is given as:

$$\frac{P_n}{P_y} = k_p \frac{1 + \alpha^2 \lambda^2}{1 + \beta \lambda^2}$$  \hspace{1cm} (28)

where

- \( P_n \) is the nominal load capacity for localized loading
- \( P_y \) is the yield load
- \( \lambda \) is the slenderness, calculated using following equation:
\[ \lambda = \sqrt{\frac{P_y}{P_{cr}}} \tag{29} \]

### 4.2 Calculation steps for \( P_n \)

Equation (1) is first used to find the \( P_y \). Equation (29) is then used to find the \( \lambda \) and Equation (28) is used to find the ratio between \( P_n \) and \( P_y \). Therefore, the following step will be used to calculate \( P_n \):

1. Using Equations (1), (3), (18), (19), (20) and (27), the yield load without iteration can be calculated.
2. Using Equation (21) for iteration calculation, each \( M_p \) for yield lines in different locations can be calculated.
3. From Equation (27), the equation can be restructured as following:
   \[ F_{SW} = \frac{1}{k_{\alpha} \tan \beta} \times \sum_{i=1}^{n} M_p k_{ui} l_i \tag{30} \]
4. Using Equations (1) to obtain the \( P'_y \) with one iteration.
5. Repeat step 2) to 4), using \( P'_y \) as input for calculating \( M'_p \) and \( P''_y \). \( P''_y \) is used for further calculation as amended \( P'_y \).
6. \( P_{cr} \) can be calculated by using Thin-wall or ABAQUS. Equation (29) is used to find the \( \lambda \) and Equation (28) is used to find the ratio between \( P_n \) and \( P_y \).
7. The load capacity \( P_n \) can be found by using \( P''_y \) times the ratio between \( P_n \) and \( P_y \).

A flow chart for covering the steps from (1) to (7) described above is shown in Figure 5.

### 5. Verification and discussion

For ITF and ETF load cases with fasteners, Table 2 provides the values of the factors required in Equation (28). The test data in following discussion is completed by using these factors and exponents. The exponents and factors for beam calculation by Glauz and Shafer [14] are also attached as a comparison.

#### 5.1 Capacity prediction: \( P_n \) vs \( P_{exp} \)

The predicted load capacities and the test results are plotted on the same graph as shown in Figure 6 for ITF and Figure 7 for ETF. Results with different internal corner radius are plotted in different colours, respectively.

For both ITF and ETF with fastener cases, the data for the smaller corner radius stocky sections shows good agreements with the predictions, while the data for the large corner radius sections indicates the predictions are conservative. This is due to the strategy for selecting the \( P_{exp} \). For smaller corner radius sections, the failure mode is due to yield-arc failure, thus the peak of the L-D curve can be observed during the controlled displacement loading. There is a limited rolling mechanism occurring in the smaller corner radius sections so the extra load capacity in negligible. However, for large corner radius sections, the rolling failure mode comes into play and gradually becomes the dominant failure mode and results in increased load capacity.

It should be noted that the chosen DSM curves also fit well the slender sections’ test data from Wu et al. [7] as shown in both the ITF and ETF graphs.

A better prediction of the full set of test data can be achieved by using a \( k_P \) factor of 1.2 as shown in Figure 8 for ITF and Figure 9 for ETF, respectively. This adjustment aims to provide better predictions for the large corner radius sections as they are easier to manufacture during the cold-forming process and more common for commercial use.

#### 5.2 Rolling mechanism and conservative prediction

Bakker and Stark [13] and later, Hofmeyer [15,16] have conducted detailed researches about the rolling mechanism in both experimental and numerical methods. The stocky section test data presented above has proved that the rolling mechanism for large corner radius sections have noticeable contributions on the bearing capacity. Given that the concept of DSM aims to provide a simple and consistent method for calculating the bearing capacity of hat sections, the precise prediction of the contribution from rolling mechanism is not covered in the \( P_y \) calculation. Based on this, the adjustment on the \( k_P \) factor is employed as a reasonable method for considering the contribution of rolling mechanism during the capacity prediction.

### 6. Conclusion and future research

The research has shown that the Direct Strength Method can be used for the design of hat sections under localised loading.

A simplified and consistent \( P_y \) model for hat sections has been proposed for use in the DSM localized loading design of hat sections by the authors based on the FE simulations and observation from the tests. In order to be consistent with the latest form of DSM equations, a general formula for DSM equation specified for hat sections under localised loading has been proposed by the author.

In terms of the test results, only stocky sections under two-flange loading cases were tested in current stage. It was concluded that the \( P_y \) model and DSM equation give
reasonable but conservative results. An explanation to the increasing of loading capacity for large corner radius sections is given that more energy can be absorbed by the rolling mechanism in large corner radius sections. Further, implementation is recommended by the authors for better capacity predictions. The DSM model is also verified with a set of historical results on slender sections. For further improvement and validation of the models and the DSM equations, experimental research on stocky sections under one flange loading cases is needed.

For experimental research on stocky sections under one flange loading cases, tests have been planned and expected to be tested in late 2022 at the University of Sydney. It would be interesting to conduct similar tests on slender sections and collect more data for improving the curves in middle to large slenderness range in the near future.

References


Figures

Figure 1 A General yield model for a vertical web (cross section view) for the ITF and ETF loading cases

Figure 2 Side view of general yield model and detail of the slope
Figure 3 Corner details of sloped web sections

Figure 4 Dimension definition for hat sections

\[ L_{TF} = L_w + 2t \]  \hspace{1cm} \text{(18)}
\[ L_{CT} = L_{TF} + 2 \times k_{dc} \times r_c \]  \hspace{1cm} \text{(19)}
\[ L_{TW} = L_{CT} + 2 \times k_{dw} \times (a - r_c) \]  \hspace{1cm} \text{(20)}

Two iterations?

Yes

\[ M_p = \frac{5E^2}{4} \]  \hspace{1cm} \text{(3)}
\[ F_{SW} = \frac{M_p}{k_{gr \tan \beta}} \times \sum_{i=1}^{n} k_{wi} L_i \]  \hspace{1cm} \text{(27)}

End

No

\[ M_p' = \frac{f_y E I_s}{4} \left[ 1 - \left( \frac{p}{f_y E I_s} \right)^2 \right] \]  \hspace{1cm} \text{(21)}
\[ F_{SW} = \frac{1}{k_{gr \tan \beta}} \times \sum_{i=1}^{n} M_p' k_{wi} L_i \]  \hspace{1cm} \text{(30)}

\[ P_y = k_w F_{SW} \]  \hspace{1cm} \text{(1)}
Figure 6 DSM curve for hat sections, ITF fastened, $k_p = 1.0$

Figure 7 DSM curve for hat sections, ETF fastened, $k_p = 1.0$
Figure 8 DSM curve for hat sections, ITF fastened, $k_p = 1.2$

Figure 9 DSM curve for hat sections, ETF fastened, $k_p = 1.2$
Figure 10 Lab testing set-ups (ITF, ETF)

Figure 11 Sample of testing specimens
Tables

Table 1 Summary of the exponents and factors for the plastic mechanism model
(F=Fastened, U=Unfastened, Y=yield line exists, N= yield line does not exist)

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Fastening Condition</th>
<th>$k_B$</th>
<th>$k_H$</th>
<th>$k_{dc}$</th>
<th>$k_{dw}$</th>
<th>$L_{TF}$</th>
<th>$L_T$</th>
<th>$L_B$</th>
<th>$L_{BF}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITF</td>
<td>F</td>
<td>2</td>
<td>0.25</td>
<td>2.5</td>
<td>2</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>ETF</td>
<td>F</td>
<td>2</td>
<td>0.25</td>
<td>2.5</td>
<td>2</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
</tbody>
</table>

$k_B$ is also known as $a/H$ or $c/H$.

Table 2 Summary of the exponents and factors for Chen’s DSM Equation (For ITF and ETF, with fasteners)

<table>
<thead>
<tr>
<th>Load Case</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>kp</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITF-F</td>
<td>0.14</td>
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<td>Beam [14]</td>
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<td>0.55</td>
<td>2</td>
<td>2</td>
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Table 3 Dimensions and testing results, slender sections (thickness = 0.7366 mm)

<table>
<thead>
<tr>
<th>Load Case</th>
<th>H (mm)</th>
<th>RIN (mm)</th>
<th>DEG (degree)</th>
<th>LB (mm)</th>
<th>$P_{max}$ (kN)</th>
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<td>ITF</td>
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<td>1.9844</td>
<td>30</td>
<td>25.4</td>
<td>7.81</td>
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<tr>
<td>ITF</td>
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<td>25.4</td>
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<td>ETF</td>
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Table 4 Dimensions and testing results (CHEN et al. 2022, Unpublished), ITF, rin = 3 mm

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<th>H (mm)</th>
<th>RIN (mm)</th>
<th>DEG (degree)</th>
<th>LB (mm)</th>
<th>$P_{max}$ (kN)</th>
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Table 5 Dimensions and testing results, ITF (CHEN et al. 2022, Unpublished), rin = 8 mm

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<th>P_max (kN)</th>
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Table 6 Dimensions and testing results, ETF (CHEN et al. 2022, Unpublished), rin = 3 mm

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Table 7 Dimensions and testing results, ETF (CHEN et al. 2022, Unpublished), rin = 8 mm

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