Study of Finite Element Analysis Type to the Nonlinear Buckling Behavior of Cellular Beams

Phattaraphong Ponsorn and Kitjapat Phuvoravan

ABSTRACT

The buckling behavior of Cellular beams with six cases of nonlinear finite element modelling has been investigated in this paper. The geometry and typical configuration of Cellular beam was referred to the design guideline of Steel Construction Institute (SCI). The finite element method was performed by using commercial software package, ANSYS Program, with solid element and nonlinear material. To ensure the accuracy result, the three cases of finite element convergence concept has been proceeded for choosing an appropriate element shape and size. The 10-node tetrahedral element approximate size of 50 mm. was validly used for the selected Cellular beams in this study. The result observation of this study show that the web-post of Cellular beam is simple to occur shear failure at high shear region due to web-post has very slender ratio, however, the beam can even withstand the uniform load further until reach the state of instability by lateral torsional buckling.

Key words: nonlinear, finite element, buckling, cellular beam

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INTRODUCTION

Cellular Beam is a circular web-opening steel beam fabricated by cutting the web of the standard hot-rolled wide flange section in pattern into two pieces and then reassemble the two halves again by welding. As a result, the beam depth is increased but leaving the circular holes at the beam web. The main advantage is that the stiffness and the strength can be increased with the same amount of material. Cellular Beam has been developed from Castellated Beam, hexagonal shape of web-opening. Cellular Beam has to use technology in cutting and welding in curves pattern, but little more effective than hexagonal web-opening in strength and serviceability. The curves of circular shape opening contribute in reducing stress concentration and fracture at the opening corners comparing to the hexagonal shape opening. Nonetheless, the utilize of both the Cellular Beam and the Castellated Beam still has more overall flexural strength and reduce deflection comparing to the original hot-rolled steel beams mainly because the overall moment of inertia is increased.

However, with the complicated shape of opening, there are additional failure modes needed to be considered. The engineers need to consider Vierendeel mechanism, web shear welding failure, web-post buckling, or even instability of the beam with lateral torsional buckling. All of these mechanism strives from the fact that the Cellular beam section is more slender.

MATERIALS AND METHODS

Both of the linear and nonlinear finite element method have been adopted to investigate the buckling behavior of Cellular Beams by using the commercial finite element software package, ANSYS v.14.5 release Program. The geometrical shape and size of the circular web-opening are referred following the design guideline publication by Steel Construction Institute (SCI), Design of Composite and Non-Composite Cellular Beams. In this study, there are six cases that have been modelling to investigate the behavior of Cellular beams as follows:

Table 1 Cases of Nonlinear Finite Element Analysis

<table>
<thead>
<tr>
<th>Case</th>
<th>Analysis type</th>
<th>Material nonlinearity</th>
<th>Geometry nonlinearity</th>
<th>Mode of initial buckling</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Static analysis</td>
<td>Nonlinear</td>
<td>Linear</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Static analysis</td>
<td>Nonlinear</td>
<td>Nonlinear</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Buckling analysis</td>
<td>Nonlinear</td>
<td>Nonlinear</td>
<td>LTB 1 time</td>
</tr>
<tr>
<td>4</td>
<td>Buckling analysis</td>
<td>Nonlinear</td>
<td>Nonlinear</td>
<td>LTB 50 times</td>
</tr>
<tr>
<td>5</td>
<td>Buckling analysis</td>
<td>Nonlinear</td>
<td>Nonlinear</td>
<td>WB 1 time</td>
</tr>
<tr>
<td>6</td>
<td>Buckling analysis</td>
<td>Nonlinear</td>
<td>Nonlinear</td>
<td>WB 50 times</td>
</tr>
</tbody>
</table>
In the first two cases, it is quite ordinarily to simulate the beams behavior because the analysis is only in-plane deformation. But in the last four cases, to simulate the nonlinear buckling behavior in ANSYS program need to be performed by using two steps of finite element analysis. The first is modelling to find the buckling modes for obtain initial geometric imperfections of Cellular beams with linear buckling analysis. The magnitude of this initial imperfection or initial deformation will approximately be 1.00 mm. Now the nonlinear buckling behavior can be analyzed by update this initial deformation into second step of analysis. Note that the magnitude of the initial deformation in each buckling modes can be more enlarged as requirement. So case 4 and case 6 have been enlarged the initial deformation to 50 times in order to obtain more obviously different behavior. The specifications and assumptions of material and methodology in this paper are provided as followings:

1. Geometry of Circular Web-Opening

The geometry of circular web-opening in this paper is referred to the design guideline of Steel Construction Institute (SCI). The basic geometry and notation for Cellular beams is shown in Figure 1. In addition, the applicable range for the shape and the size of circular opening are given in Equation 1 and Equation 2. The ratio of shape and size of this study is that the Cellular beam have S/D₀ = 1.08 and D/D₀ = 1.49

![Figure 1](image)

**Figure 1** Basic geometry and notation used for Cellular Beams by SCI guideline

\[
\begin{align*}
1.08 < S / D_0 < 1.5 \\
1.25 < D / D_0 < 1.75
\end{align*}
\] (1) (2)

Where

- \(S\) = Pitch length of opening
- \(D\) = Depth of Cellular Beam
- \(D_0\) = Diameter of opening
2. Configuration of Cellular Beam

The configuration of Cellular Beam in this study is CB-600x200x8371.57 (D = 600, D₀ = 400, bᵣ = 200, tᵣ = 13, tₓ = 8, L = 8371.57 mm.), which the section height was enhanced 1.5 times from hot-rolled I-section standard steel beam, W400x200x66 mm. (Figure 2). The length of Cellular Beam fabricated from a commercial standard steel beam of 9000 mm. length will eventually be 8371.57 mm. due to the trimming of the scrap portions at both ends. Usually, the Cellular beams may has the infill circular plates welded into the hole at both ends in order to better resist the imposed concentrated loads or reactions at both ends. The configuration of beam used in this study is a simply supported beam with the uniform pressure load applying at the top flange surface.

Figure 2 Typical of Cellular Beam and standard steel beam with curved cut pattern.

3. Nonlinear Material Model for Structural Steel

A bi-linear stress strain curve has been applied to simulate the elastic-perfectly plastic behavior of steel structure material nonlinearity for using in this finite element analysis. The material properties used from ANSYS material library are Young’s modulus of 2x10⁵ MPa., Poisson’s ratio of 0.3, shear modulus of 7.6923x10⁴ MPa., yield strength of 250 MPa. and the tangent modulus of 1x10⁻¹⁴ MPa., as show in Table 2

<table>
<thead>
<tr>
<th>Properties of Structural Steel Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus (MPa)</td>
</tr>
<tr>
<td>2x10⁵</td>
</tr>
</tbody>
</table>

4. Finite Element Modelling

The solid element from ANSYS element library has been used in this finite element analysis. The concept of finite element convergence has been performed to find an appropriate element type and size to accurately model the Cellular Beams behavior (Figure 3). The results of three cases of finite
element convergence, deflection convergence, stress convergence and critical buckling load convergence, show that the number element of approximately 10000 elements is appropriate. In other words, meshing with the solid187 10-node tetrahedral element approximate size of 50x50 mm. (Figure 4d) is practicably valid to use for the selected Cellular Beam in this study.

Figure 3 Result of finite element convergence of solid186 20-node hexahedral element and solid187 10-node tetrahedral element (a) deflection convergence (b) stress convergence (c) critical buckling load convergence (d) meshing with solid187 10-node element size of 50x50 mm.

RESULTS AND DISCUSSION

The five cases results of finite element analysis are tabulated in table 3. Case 1 is a linear analysis, only material nonlinearity in inelastic range with in-plane deformation behavior, show the uniform load of 9.96 kN/m occurred the first yield at both ends web-post which are high shear region. For case 2, additional nonlinear analysis by large displacement conception, also show the first yield at uniform load of 9.95 kN/m at web-post as case 1. Both of these two static in-plane analysis type has stiffness and behavior similar as each other (Figure 4a). For the types of nonlinear buckling analysis, case 3, 4, 5 and 6 (Figure 5, 6 and Figure 7), the result show the uniformed load at first yield 9.13, 8.16, 9.05 and 6.48 kN/m and at ultimate uniformed load 15.22, 11.12, 15.44 and 15.25 kN/m respectively. When compare the cases of lateral torsional buckling mode in the initial deformation, case 3 and case 4, the result show that case 4 which has large initial imperfection is more effect to greatly reduce stiffness and load capacity of Cellular beam. Denote that the dash line is indicated the 50 times of initial
Table 3 Result of nonlinear finite element analysis

<table>
<thead>
<tr>
<th>Case</th>
<th>Load at first yield (kN/m)</th>
<th>Load at ultimate (kN/m)</th>
<th>Plastic strain at ultimate load (mm/mm)</th>
<th>Region of maximum plastic strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>9.96</td>
<td>-</td>
<td>-</td>
<td>web-post</td>
</tr>
<tr>
<td>Case 2</td>
<td>9.95</td>
<td>-</td>
<td>-</td>
<td>web-post</td>
</tr>
<tr>
<td>Case 3</td>
<td>9.13</td>
<td>15.22</td>
<td>0.0035</td>
<td>web-post + top flange</td>
</tr>
<tr>
<td>Case 4</td>
<td>8.16</td>
<td>11.12</td>
<td>0.0016</td>
<td>web-post + top flange</td>
</tr>
<tr>
<td>Case 5</td>
<td>9.05</td>
<td>15.42</td>
<td>0.0035</td>
<td>web-post + top flange</td>
</tr>
<tr>
<td>Case 6</td>
<td>6.48</td>
<td>15.25</td>
<td>0.0059</td>
<td>web-post + top flange</td>
</tr>
</tbody>
</table>

Figure 4 Graphs of nonlinear finite element analysis (a) uniform load against in-plane deflection at midspan (b) uniform load against lateral deflection (c) uniform load against plastic strain
deformation. In both case 5 and case 6 that have web-post buckling mode in the initial deformation show case 6 also has less stiffness than case 5 because of the difference in large initial imperfection. Nevertheless, reminding that case 5 and case 6 that have initial deformation is web-post buckling mode which will be occur in latter mode. All of these four cases has difference of stiffness and behavior in early loading due to the magnitude of initial imperfection and initial buckling mode. All cases has been fully yielding at both ends web-post by shearing and finally has to take the state of instability by lateral
torsional buckling that effect to the load has rapidly decreased meanwhile the maximum plastic strain relocated from both ends web-post to the top compression flange at midspan. The theoretical critical buckling load of the same beam but none of web-opening following the American Institute for Steel Construction AISC is 24.47 kN/m. But, however, the theoretical analysis equation is not appropriated for Cellular beam due to present of web-opening along the beam. So the finite element analysis has been performed to evaluate the elastic critical buckling load, 15.14 kN/m. The ultimate uniformed load that case 3, case 5 and case 6 reach the lateral torsional buckling load are also similar and approximate to linear elastic critical buckling load obtaining from finite element analysis (Figure 4b).

Figure 5 Case 3 result of nonlinear buckling analysis (a) initial deformation (b) deformation at ultimate loading (c) plastic strain

Figure 6 Case 4 result of nonlinear buckling analysis (a) initial deformation (b) deformation at ultimate loading (c) plastic strain

Figure 7 Case 6 result of nonlinear buckling analysis (a) initial deformation (b) deformation at ultimate loading (c) plastic strain
However, there are also the other factors in this study may affect to the nonlinear buckling behavior of Cellular beams such as ratio of shapes and sizes of circular web-opening, loading case condition, restrain of support, different beam spans and sections, type of other element or even assumption of nonlinear material for strain-hardening behavior, which should be further more studies in the future research.

CONCLUSION

The nonlinear finite element analysis investigating the buckling behavior on the five cases of Cellular beams are summarized as follows:

1. In static in-plane analysis type, case 1 and case 2, the analysis result has shown that there are almost no effect to the Cellular beam when comparing with small displacement concept and large displacement concept.

2. In cases of nonlinear buckling analysis with mode of initial buckling is lateral torsional buckling, case 3 and case 4, the analysis result has been shown that increasing the initial deformation to 50 times has greatly effect to reduce stiffness and load capacity.

3. In cases of initial buckling mode is web-post buckling, case 5 and case 6, the analysis result has been shown that the large initial geometrical imperfection has influence to reduce stiffness.

4. In case 5, the Cellular beam which has set the web-post buckling to initial buckling mode has capacity to full yielding at web-post and then the beam can resist the uniformed load to ultimate loading before reaching instability by lateral torsional buckling as well as case 3.

5. Compare static analysis and nonlinear buckling analysis, the result has been shown that the beams with slender section such as Cellular beam must has been inevitably encounter the nonlinear buckling behavior. These nonlinear buckling behavior will be influenced effect to greatly reduce stiffness and load capacity of Cellular beam, especially, by lateral torsional buckling.

REFERENCES

ANSYS. 2010. ANSYS Mechanical Structural Nonlinearities Release 12.1. ANSYS, Inc. Proprietary