An Experimental Study on Inelastic Lateral-Torsional Buckling Strength of Monosymmetric Stepped I-Beam Subjected to a Concentrated Load

Yi Seul Park and Jong Sup Park

1, First Author
Master of Science, Sangmyung University, yiseulpark@rist.re.kr

*2, Corresponding Author
Associate Professor, Sangmyung University, jonpark@smu.ac.kr

Abstract
This paper extends the study made on determining the inelastic lateral torsional buckling strength of monosymmetric stepped I-beam in consideration of its degree of monosymmetry by making a destructive test while subjecting the beam to a concentrated load. Prior to the test, numerical values of the expected results are estimated by finite element analysis using the program ABAQUS. The numerical results are estimated by creating a model which experiences the same conditions as that of the test specimen. Then, a comparison is made with the experimental results, the results from the proposed equation and the results from the finite element analysis. In succession, the safety and economic feasibility of the proposed equation is evaluated. Finally, the comparisons made showed that the proposed equation yielded results that are acceptable and has values that are similar to the values yielded by the test. More tests are needed to determine if the proposed equation is also suitable for other loading conditions.

Keywords: Inelastic Lateral Torsional Buckling, Stepped Beam, Beam Design, Experimental Study

1. Introduction

The use of stepped I-beams in construction has been in effect for the past few years. However, there are only a few studies made in determine its strength and most of these studies focused on the elastic range and dealing with doubly symmetric stepped I-beams. Some of these studies are made by Gelera and Park [5] and Park and Stallings [6]. Meanwhile, Park [7] made a study on the inelastic lateral torsional buckling strength of monosymmetric stepped I-beam and suggested different equations to be used for both doubly stepped beams, DSB, and singly stepped beams, SSB, depending on the loading condition and the number of inflection points as well as the degree of monosymmetry. Figure 1 shows a diagram for stepped beams in bridges.

Fig. 1 Stepped Beams in Bridges

The aim of this research is to conduct a real life experiment on a monosymmetric stepped I-beam specimen subjected to a concentrated load to determine if the suggested equation made by Park [7] produces results that has acceptable values in comparison with the results produced by the experiment and by the finite element analysis. After the comparisons, certain conclusions and recommendations are made.

2. Background and Previous Studies

The inelastic lateral-torsional buckling strength in the AISC [2] is proposed to be calculated by the following equation:

\[ M_{in} = C_b \left[ M_p - (M_p - 0.7F_p S_{le}) \left( \frac{l_{l} - l_p}{l_{l} - l_{r}} \right) \right] \leq M_p \]  \hspace{1cm} (1)
Where \( M_p \) = plastic moment, \( L_p \) and \( L_r \) = limiting length for inelastic range, \( L_b \) = unbraced length and \( F_y \) = minimum yield stress of the type of steel being used. \( C_b \) in the equation is given as:

\[
C_b = \frac{12.5M_{max}}{2.5M_{max} + 3M_A + 4M_B + 3M_c} R_m \leq 3.
\]

Where \( R_m = [0.5 + 2(I_{yc}/I_y)^2] \). \( R_m \) denotes the parameters of the uniaxial symmetry where \( I_y \) is the moment of inertia about the y-axis, \( I_{yc} \) is the moment of inertia of the compression flange about the y-axis. If the cross-section of the beam has biaxial symmetry then a value of 1 is used for \( R_m \). \( M_{max} \), \( M_A \), \( M_B \) and \( M_C \) are the maximum moment, moment at \( \frac{1}{4} \) point, moment at \( \frac{1}{2} \) point and moment at \( \frac{3}{4} \) points along the unbraced length of the beam.

Meanwhile, a study made by Park [7] proposed the following equation to be used to calculate the inelastic lateral torsional buckling strength of monosymmetric stepped I-beams subjected to pure bending moment.

\[
M_{m} = C_{m} M_{tr}^m
\]

Where \( M_{m}^{\text{at}} \) is the inelastic lateral torsional buckling strength of the prismatic beam having the smaller cross section and \( C_{m}^{\text{at}} \) is the stepped beam correction factor to take account for the effect of steps in the inelastic lateral torsional bucklings strength of monosymmetric stepped I-beams. \( C_{m}^{\text{at}} \) is given as:

\[
C_{m}^{\text{at}} = 1 + 1.1\alpha^{0.7}(\beta\gamma^{0.6} - 1) \quad \text{for DSB with } \rho = 0.1 \text{ and } 0.9
\]

\[
C_{m}^{\text{at}} = 1 + 1.1\alpha^{0.7}(\beta\gamma^{0.7} - 1) \quad \text{for DSB with } \rho = 0.3 \text{ and } 0.7
\]

\[
C_{m}^{\text{at}} = 1 + 1.1\alpha^{0.7}(\beta\gamma^{0.7} - 1) \quad \text{for SSB with } \rho = 0.1 \text{ and } 0.9
\]

\[
C_{m}^{\text{at}} = 1 + 0.8\alpha^{0.7}(\beta\gamma^{0.7} - 1) \quad \text{for SSB with } \rho = 0.3 \text{ and } 0.7
\]

Where DSB and SSB refers to doubly stepped beam and singly stepped beam respectively, \( \rho \) refers to monosymmetric ratio which is defined as \( I_{yc}/I_y \) and \( \alpha \) is the ratio of the stepped lengths of the smaller to larger section, \( \beta \) and \( \gamma \) are the ratios of the flange widths and flange thickness of the larger to smaller section respectively.

Other equations proposed by Park [7] that takes into account the effect of varying moment on the inelastic lateral torsional buckling strength of monosymmetric stepped I-beam are presented below:

\[
M_{m} = C_{m} M_{tr}^m
\]

\[
C_{m} = f(\rho) C_{b}^{m}
\]

Where \( C_{m}^{\text{at}} \) = the moment gradient factor to account for the effect of varying moment on the inelastic lateral torsional buckling strength of the stepped beams. Meanwhile the values for \( C_{b}^{m} \) and function of \( \rho \) are given in table 1 which are dependent on the number of inflection points:

<table>
<thead>
<tr>
<th>IP</th>
<th>( C_{b}^{m} )</th>
<th>( f(\rho) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>[ \frac{12.5M_{max}}{2.5M_{max} + 3M_A + 4M_B + 3M_c} ]</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>[ \frac{12M_{max}}{2M_{max} + M_A + 3M_B + M_c} ]</td>
<td>( \rho^3 - \rho^2 - \rho + 1.625 )</td>
</tr>
<tr>
<td>2</td>
<td>[ \frac{10M_{max}}{3M_{max} + 2M_A + 6M_B + 2M_c} ]</td>
<td>1</td>
</tr>
</tbody>
</table>
3. Experiment

The destruction experiment conducted to investigate the inelastic lateral torsional buckling strength of monosymmetric stepped I-beam used an I-beam model specimen of uniaxial symmetry. The specimen used is under the same conditions as that model used in the finite element analysis to get an accurate comparison of results. The experiment investigates the consistency of the structural behavior and failure modes of specimen. The specimen is also made according to standard laboratory models for experiments to have a more reliable evaluation of the results.

3.1 Material Tensile Test

A test is conducted to determine the elastic modulus and yield stress of the specimen before doing starting the experiment. The standards followed for testing the material is that of the American Society of Testing Materials (ASTM) E8/E8M. Three specimens (SP1, SP2, SP3) having a gauge length of 50mm SS400 steel plate each are obtained by cutting the wires from the substrate plate tester. The static material tensile tests are performed at a loading rate of 3mm/sec with 200tf on a Universal Test Machine (UTM). Shown below is figure 2 which represents the results of the static tensile test in a stress-strain graph and table 2 which show the elastic modulus and yield stress for each tests. Properties of SS400 steel and obtained similar values as a result of the following properties of the specimens are:

![Figure 2. Stress-strain curves of material tensile tests](image1)

![Figure 2. Stress-strain curves of material tensile tests](image2)

![Figure 2. Stress-strain curves of material tensile tests](image3)

Table 2. Material properties of Tensile Specimens

<table>
<thead>
<tr>
<th>Property</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic Modulus</td>
<td>207.1</td>
<td>214.0</td>
<td>182.6</td>
</tr>
<tr>
<td>(GPa)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield Stress</td>
<td>270.9</td>
<td>282.5</td>
<td>270.6</td>
</tr>
<tr>
<td>(MPa)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.2 Experimental Model

The experimental model selected is made by Hyundai Steel. It is an H-beam having a cross-section of 150 × 75 and a monosymmetric ratio (ρ) of 0.7. The unsupported length (Lb), according to cross-section and cross-section characteristics of the experimental model is shown in Figure 3. The curve on Fig. 4 is based on the AISC Specifications [2] showing the nominal flexural strength of a beam as a function of its unbraced length. X-axis represents the unsupported length (Lb, m) and Y-axis represents the nominal moment (Mn, kN-m). The specimens observed are denoted by the points located on the curve. Also, the locations of the strain gages placed on the beams are shown in figures 5 and 6.
3.3 Nominal Strength Using Finite Element Analysis and Proposed Equations

First, the analysis is made on a doubly stepped beam (DSB) with a change in cross-section at both ends. The intermediate values of the parameters are given as: \( \alpha = 0.25, \beta = 1.0, \gamma = 1.4 \). The residual stress experienced by the beam was assumed to be a simple triangular distribution and the initial lateral displacement of 0.3% was applied based on domestic I-beam standard dimension tolerance from Hyundai Steel (2006) as shown in figure 8. The modulus of elasticity used is 210GPa and the yield stress used is 280MPa. Then, table 2 shows the comparisons and the percentage between the values yielded by the proposed equation and by the finite element analysis. PL1 represents a prismatic monosymmetric beam and DL1 represents the doubly stepped monosymmetric beam.

4. Experimental Results and Comparisons

Figures 9, 10, 11 and 12 show the comparisons of the values obtained using experimental analysis, non-linear analysis and static analysis. Figures 9 and 10 present the graph consisting of an ordinate as a function of the load and the abscissa as a function of the compressive strain. Meanwhile, figures 11 and 12 have their abscissa as a function of the tensile strain experienced by the beam. The figures show the consistency of the structural behavior as the load increases and its failure modes. The experimental analysis uses beam having the same state as that of used in the nonlinear and static analysis. Also, PL1 corresponds to prismatic monosymmetric beam used while DL1 represents the doubly stepped beam.
used. Then, TR and TR1 represent the location of the strain gages analyzed at top flange as shown in Fig. 5 and BR and BR1 represent the location at the bottom flange. Figures 13 and 14 show failure shapes of prismatic and doubly stepped beams with singly symmetric section.

Table 3 shows the numerical values of the analysis made and the percentage for each comparison. It can be observed that the maximum difference is about 10% between the experimental result and the finite element analysis and 9.6% between the proposed equation and the experimental result. Thus, it can be said that the proposed equation gives acceptable results.

Figure 9. Result of PL1 at TR

Figure 10. Result of DL1 at TR1

Figure 11. Result of PL1 at BR

Figure 12. Result of DL1 at BR1

Figure 13. Failure shape of monosymmetric prismatic specimen

Figure 14. Failure shape of monosymmetric doubly stepped specimen
Table 3. Comparisons of results from test, FEA, and proposed equation

<table>
<thead>
<tr>
<th>Model</th>
<th>Test (kN-m)</th>
<th>FEA (kN-m)</th>
<th>Comparison (%)</th>
<th>Eq.(8)</th>
<th>Comparison (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PL1A</td>
<td>28.20</td>
<td>31.50</td>
<td>10</td>
<td>31.18</td>
<td>9.6</td>
</tr>
<tr>
<td>DL1B</td>
<td>30.49</td>
<td>33.50</td>
<td>9</td>
<td>33.67</td>
<td>9.4</td>
</tr>
</tbody>
</table>

5. Conclusions

The aim of this study is to determine the reliability of the proposed equations that have been studied in determining the inelastic lateral torsional buckling strength of a monosymmetric stepped I-beam subjected to a concentrated load at midspan. In order to do this, destructive tests are conducted on specimens having the same property and behavior as the one used in formulating the proposed equations. Three different comparisons are made and the values obtained from these comparisons are evaluated. First is the comparison of the finite element analysis and the proposed equation. The comparison showed that the difference between the inelastic lateral torsional buckling strength using the finite element analysis and the equation yielded a maximum difference of -1%. Second is the comparison between the finite element analysis and the experimental results. This comparison yielded a maximum difference of 10%. Finally, the comparison between the suggested equation and the experimental study showed a maximum difference of 9.6%. Thus, it can be concluded that, based on the tests performed, the suggested equation yielded acceptable results in determining the inelastic lateral torsional buckling strength of a monosymmetric stepped I-beam subjected to a concentrated load at midspan.

Further study can be made by subjecting the test specimen into other loading conditions and by using singly stepped beams to check the reliability of the other equations. Also, determining the exact geometrical imperfection and residual stress of the beam to be used for the next test can also be made so as to avoid possible errors due to assumptions.

6. Acknowledgement

Results contained herein were obtained in connection with a research project supported by the Sangmyung University. The funding, cooperation and assistance of many people, in specialty, Sung Yong Kang, from the organization is gratefully acknowledged.

7. References