Comparative study between 2D seismic design methods for steel bridge piers with circular cross-section

Kohei Hashimoto¹, Akira Kasai² and Kulkarni³

¹ Kumamoto University, Kumamoto, Japan, 128d8823@st.kumamoto-u.ac.jp
² Kumamoto University, Kumamoto, Japan, kasai@kumamoto-u.ac.jp
³ Nagoya University, Nagoya, Japan, kulkarni@civil.nagoya-u.ac.jp

Abstract
This study is aimed at developing seismic design methods for steel bridge piers with circular cross-section. For this purpose, this paper deals with the cyclic elastoplastic large displacement FE analysis of uniform thickness circular steel columns. The cyclic uni-directional and elliptical/circular bi-directional loading patterns with constant axial force are applied to the columns. The effect of gradual change in loading pattern on the strain behavior in shell and beam element models is observed. The parametric study is carried out and based on the ultimate average compressive strain in the beam element models. Finally, the ductility formulas are developed separately for uni-directional and circular bi-directional loading cases.

Keywords: Steel bridge pier, Strain-based seismic design, Displacement-based seismic design, Cyclic behavior

1. INTRODUCTION
The ultimate strain formulas were proposed already for steel short-cylinders under various loading conditions [1]. However, it should be noted that in these studies the steel short-cylinders are assumed as critical segments of the bridge piers as shown in Fig. 1 for a cantilever pier and portal frame. Therefore, to investigate the ductility capacity in terms of strain, loading conditions such as pure compression, combined compression and bending, combined bending and axial force fluctuation were applied monotonically on short-cylinders. Whereas, in the case of ductility prediction in terms of displacement, cyclic uni-directional or bi-directional loadings have been applied on the full length steel columns [2]. This means effect of cyclic loading on the behavior of critical segments in the bridge piers has not been estimated so far. Seismic design method based on displacement-based capacity was proposed and explained about how to confirm performance of circular steel columns under simultaneous bi-directional earthquake motions. And it was concluded that strain-based seismic design method for circular steel columns under cyclic bi-directional loading is essential to develop, so as to check its performance with formerly proposed displacement-based method. Therefore, objective of this study is to develop ultimate strain formulas and based on that seismic design method for circular steel bridge piers when subjected to uni- as well as bi-directional cyclic loading.
Further the ultimate strain formulas are proposed for uni- and bi-directional loading based on the results of parametric study. The seismic design procedure is developed and verified by one and two directional

Fig. 1 Critical Segments in Bridge Pier
nonlinear dynamic analysis.

2. NUMERICAL METHOD
The material properties of steel grade SM490 are employed through M2SM [3] constitutive law. The cyclic uni- and bi-directional loadings similar to that shown in Fig. 2 are applied to the top node of FE models with constant axial force. FE model of steel circular columns are analyzed by applying constant axial downward force and lateral cyclic displacement loading as shown in Fig. 3 using the ABAQUS program [4]. The material and geometric nonlinearities are also considered. Here the beam element models are employed, because in engineering practices, to check dynamic performance of bridge systems beam elements are usually selected for modeling. It should be noted that, as the shell element model of bridge pier judges the local buckling in the base part, the beam element model ignores the local buckling effect; however, axial stress and strain in these elements are measurable. Therefore, instead of shell element model, the strain is observed from beam element models to develop the ultimate strain formulas. Hence, the numerical analyses are carried out for these two types of FE models by applying horizontal cyclic displacement loadings and constant axial force. Further, it is important to point out that strength and equivalent strain are measured from shell element models and average compressive strain are taken from the beam element model, so that behavior of both types of FE models is automatically get included in the ultimate strain formulation which is discussed in the following section.

3. CONCEPT OF ULTIMATE STRENGTH AND ULTIMATE STRAIN
The shell element models of steel columns are purposefully selected to include the local buckling effect into the ultimate strength quantity. However, ultimate strain values are measured from average compressive strain in the beam element models. Because, even if the concept of equivalent strain incorporate local buckling, this concept is based on nodal deformation in the direction parallel to column height and not on the stress-strain behavior within individual shell element. On the other hand, average compressive strain concept represents stress-strain relationship at each integration point in the cross-section of beam element. Further, in most of the dynamic analysis, instead of shell elements, beam elements are
generally preferred by engineers to construct the FE models of bridge systems which decrease complexity in modeling and also reduce analysis run time. Hence, concepts of FE modeling used in static analysis to predict the capacity and in dynamic analysis to find the demand both synchronize well with each other. The strength envelop curve can be plotted as shown in Fig. 4 (a) and the ultimate strength is defined at 95% of maximum strength on post peak curve. Envelop curves for equivalent strain factor \( \frac{\varepsilon_{\text{ms}}}{\varepsilon_y} \) and average compressive strain factor \( \frac{\varepsilon_{\text{mb}}}{\varepsilon_y} \) are obtained from shell and beam element models respectively and are plotted as shown in Fig. 4 (b). The ultimate strain factors \( \frac{H_{95}}{H_y} \) and \( \frac{\varepsilon_{\text{ms},95}}{\varepsilon_y} \) are the points on strain envelop curves corresponding to the ultimate strength factor \( \frac{H_{95}}{H_y} \). Moreover, in Fig. 4 (b), it is observed that, the ultimate equivalent strain has higher amplitude than that of average compressive strain. This difference is appeared due to local buckling in shell element model and which is ignored in the beam element model. Above described procedure of ultimate strain evaluation is applied for each model mentioned in Table 1 to find out influence of various parameters.

### Table 1 Properties of Circular steel Columns

<table>
<thead>
<tr>
<th>Columns</th>
<th>( R_t )</th>
<th>( \lambda )</th>
<th>( D ) (mm)</th>
<th>( h ) (mm)</th>
<th>( t ) (mm)</th>
<th>( L_e ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P50-20</td>
<td>0.050</td>
<td>0.20</td>
<td>789</td>
<td>2152</td>
<td>20</td>
<td>256</td>
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<td>789</td>
<td>4303</td>
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<td>256</td>
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<td>P50-60</td>
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<td>6455</td>
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<td>256</td>
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<td>0.20</td>
<td>942</td>
<td>2582</td>
<td>20</td>
<td>285</td>
</tr>
<tr>
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<td>5164</td>
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<td>285</td>
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<tr>
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<tr>
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<td>3227</td>
<td>20</td>
<td>324</td>
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<tr>
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<td>1173</td>
<td>9681</td>
<td>20</td>
<td>324</td>
</tr>
</tbody>
</table>

### 4. EFFECT OF LOADING PATTERNS ON ULTIMATE STRAINS

To understand the effect of bi-directional cyclic loading on ultimate behavior of both shell and beam element models, seven loading patterns are selected by substituting \( b/a = 0, 0.1, 0.25, 0.5, 0.75, 0.9, 1 \) in Eqs. (1) and (2), which include uni-directional (UNI) and perfectly circular bi-directional (CIR) patterns.

(a) Progressing in positive X direction

\[
\begin{align*}
\frac{U_x}{\bar{\delta}_y} &= -\left( 1 - \frac{n}{2} \right) \cos(n \pi) \\
\frac{U_y}{\bar{\delta}_y} &= -\frac{b}{a} \left( 1 - \frac{n}{2} \right) \sin(n \pi)
\end{align*}
\]  

(1)
(b) Progressing in negative X direction

\[
\frac{U_x}{\delta_y} = n \cos(\pi) \\
\frac{U_y}{\delta_y} = \frac{b}{a} n \sin(\pi)
\]  

(2)

Only one axial force case $P/P_y = 0.15$ is taken here to explain this effect of loading pattern.

The graphs are plotted for the ultimate strains normalized by ultimate strains for UNI loading versus $b/a$ and for each radius-thickness ratio separately as illustrated in Fig. 5. Left side graphs are shown for equivalent strain ratio i.e. $\bar{\varepsilon}_{ms.95}/\bar{\varepsilon}_{ms.95}^{uni}$ whereas, right side graphs are for average compressive strain ratio i.e. $\bar{\varepsilon}_{mb.95}/\bar{\varepsilon}_{mb.95}^{uni}$. Some

Fig. 5 Effect of Loading Patterns on Ultimate Strain Ratios
significant observations from these plots are summarized as follows;
(a) The effect of ratio \( b/a \) on the behavior of ultimate equivalent and average compressive strain factors has shown considerable similarity. This implies that, shell element model and beam element model perform in similar way almost for all cases of the columns demonstrated in Fig. 5.
(b) In each graph of Fig. 5, it is observed that as the loading pattern changes from \( b/a = 0 \) to \( b/a = 1 \), ultimate strain for the short columns (i.e. \( \bar{\lambda} = 0.2 \)) goes on decreasing than its uni-directional ultimate strain. Whereas, for the medium and long columns (i.e. \( \bar{\lambda} = 0.4, 0.6 \)) that respectively remains nearly constant and increases gradually. This means, slenderness ratio is an important parameter in ultimate behavior of the columns and which further involves its significance in the ductility formulation.

5. DUCTILITY FORMULATION AND SEISMIC DESIGN METHOD

5.1. Ultimate Strain Formulas
The ultimate strain formulas developed for steel columns so far, were concerned to the strain behaviour in the critical part effective failure height region. Therefore, the effect of the entire height of the column i.e. the slenderness ratio was neglected in ultimate strain formulation. However, in the present work, it is found that slenderness ratio parameter has significant effect on the ductility behavior of steel columns. Therefore, \( R, \bar{\lambda} \) and \( P/P_y \) are very important parameters to get involved in ultimate strain formulas. Moreover, in the past study, the FE models using shell elements were constructed for the critical part of the column and analyzed for compression and bending loads so as to consider local buckling effect in the ductility formulation. Whereas, in the present work, the ultimate strain formulas are derived from the strain observations of beam element models which ensures coordination between FE modeling used in the ductility prediction process and seismic design process i.e. dynamic analysis. The ultimate average compressive strain factors \( \bar{\varepsilon}_{mb,95}/\varepsilon_y \) and \( \bar{\varepsilon}_{mb,95/CIR}/\varepsilon_y \) are plotted against a combined value of \( R, \bar{\lambda} \) and \( P/P_y \) as shown in Figs. 6 (a) and (b), respectively.

![Fig. 6 Proposed Ultimate Strain Formulas for Circular Steel Bridge Piers](image_url)
These combined values are determined from the nonlinear regression analysis. Eqs. (3) and (4) are written for ultimate strains in UNI and CIR loading cases fitted for 99% and 97% confidence levels respectively.

\[ \frac{\bar{e}_{\text{ub},95|\text{UNI}}}{e_y} = \frac{1}{(0.29 - P/P_y)^{0.24} R_y^{0.21} \lambda^{0.12}} \pm 4.13 \leq 20.0 \]  

(3)

\[ \frac{\bar{e}_{\text{ub},95|\text{CIR}}}{e_y} = \frac{(0.93 + P/P_y)^{0.71} \lambda^{0.31}}{R_y^{1.06}} \pm 3.04 \leq 20.0 \]  

(4)

Valid for the ranges, 0.05 \leq R_y \leq 0.09, 0.2 \leq \lambda \leq 0.6 and 0.0 \leq P/P_y \leq 0.2.

The dashed lines in Fig. 6 are the lower bound and upper bound levels for the proposed equations and it is recommended here, to select the lower bound values from Eqs. (3) and (4) which will provide the minimum ultimate strain for the steel circular columns under UNI and CIR loading. In these equations maximum limit for ultimate strain is set to 20.0 because, in case of the higher failure strain, low cycle fatigue may initiates in the material. In other words, ultimate strain which is in fact an average compressive strain, if exceeds this limit, the local maximum strain would be very large and such numerical results would become unreliable. Hence, the upper bound for ultimate strain is limited to 20.0[5].

5.2 Strain-based Seismic Design Method

It is well known that the earthquake generates multidirectional motions in the ground; therefore it is important to verify structural response due to more than one simultaneous earthquake components. Similar to the previously proposed displacement-based seismic design method[6], the strain-based seismic design method is proposed here with considering the ultimate strain equations for UNI and CIR loading i.e. Eqs. (3) and (4) respectively. The step by step procedure of this method is indicated in Fig. 6 and explained as follows,

(1) As explained in previous chapter, the present seismic design method is an extension to the conventional uni-directional design method, hence in first step, apply the earthquake motions in longitudinal and transverse directions to the structure and check whether the maximum response of average compressive strain in the effective failure region \( L_y \) of the column remains within the ultimate strain limit calculated by Eq. (3).

(2) If the column confirms Step (1), then apply earthquake motions in both directions simultaneously, and again check that the maximum average compressive strain response is less than the ultimate strain value from Eq. (4).

(3) At any step, if the column does not satisfy the condition then it is recommended to upgrade or redesign the column. The functionality of this strain-based seismic design method and comparison with the formerly proposed displacement-based design method, are explained through some illustrative examples of nonlinear dynamic analysis in the following sections.
6. SUMMARY

This paper also deals with the cyclic elastoplastic large displacement FE analysis of uniform thickness circular steel columns. Two types of FE models are constructed namely (1) shell element model which accounts for local buckling and (2) beam element model where local buckling is absent. The uniaxial and multiaxial M2SM are used for nonlinear material properties of beam and shell elements respectively. The cyclic uni-directional and elliptical/circular bi-directional loading patterns with constant axial force are applied to the columns. The effect of gradual change in loading pattern on the strain behavior in shell and beam element models is observed. The parametric study is carried out and based on the ultimate average compressive strain in the beam element models, the ductility formulas are developed separately for uni-directional and circular bi-directional loading cases. Further, the strain-based seismic design method is proposed and it compared with displacement-based method by performing some nonlinear dynamic analysis. Following are the concluding remarks drawn from this study.

(a) The effect of gradual change in loading pattern from purely uni-directional to elliptical and then to circular bi-directional showed that ultimate strains in shell and beam element models behave in similar manners.
(b) Moreover, it is also observed that the short column with circular bi-directional loading losses its ductility considerably.
faster than with uni-directional loading.

c) This implies that the slenderness ratio plays an important role in the ultimate behavior of steel circular columns and hence becomes necessary to include in the ductility formulation.

d) The ultimate strain formulas are developed by curve fitting method, based on the observations of ultimate states of the beam element models, instead of shell element model, because it synchronizes the FE modeling technique used in dynamic analysis and ductility prediction by static analysis. The seismic design method for bi-directional earthquake is proposed based on the ultimate strain formulas.

7. REFERENCES


