SEISMIC CAPACITY OF STEEL CIRCULAR COLUMN SUBJECTED TO BI-DIRECTIONAL HORIZONTAL MOTIONS

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1. Introduction:

After the Kobe Earthquake in 1995, the specifications for the highway bridges were significantly revised in Japan. According to this specifications[1], the bridge is analyzed for independent longitudinal and transverse earthquake motions without considering the possibility of maximum amplitude of acceleration when bi-directional earthquake motions are applied. Various studies[2] on effect of bi-directional earthquake motions on the steel as well as reinforced concrete bridge pier were carried out in past. However, in the present study, seismic capacity of the circular steel column is observed. Torii[3] proposed a design method for steel bridge pier subjected to bi-directional horizontal earthquake motion and suggested the elliptical displacement pattern for complex displacement locus of pier apex, obtained from bi-directional earthquake motions, as shown in figure 1. The performance of thick circular steel column with respect to applied elliptical displacement is observed in detail in this study.

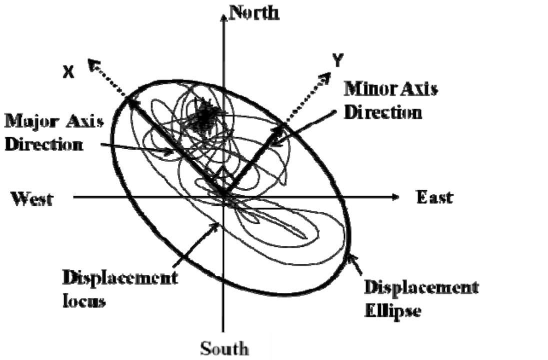

Figure: 1 Displacement locus of pier apex and Displacement ellipse

2. Analytical model:

For constructing the FEM model of steel circular column, shell and beam elements are used with modified 2 surface model for steel type SM490 (Table 1, Table 2). The bottom height of 3D (D=diaphragm interval=outer diameter of pier) is made up of shell elements and remaining height of pier is made up of beam elements. The height interval up to first diaphragm is meshed in to 30 segments in axial direction as well as in circumferential direction, while remaining two intervals are also divided in to 30 segments axially and 5 in circumferentially. The beam element is divided in to 10 segments as shown in figure 2. The radius thickness ratio and slenderness ratio are calculated by the following equations.

$R_t = \sqrt{3(1-\nu^2)}(\sigma_y/E)(d/2t)$, $\bar{\lambda} = (2h/r)(1/\pi)\sqrt{\sigma_y/E}$ where, h=height of pier, d=(D-2t)=diameter of pipe section, t=thickness of pier. The UP100-40 model means the steel unstiffened pipe having 0.1 radius thickness ratio and 0.4 slenderness ratio.

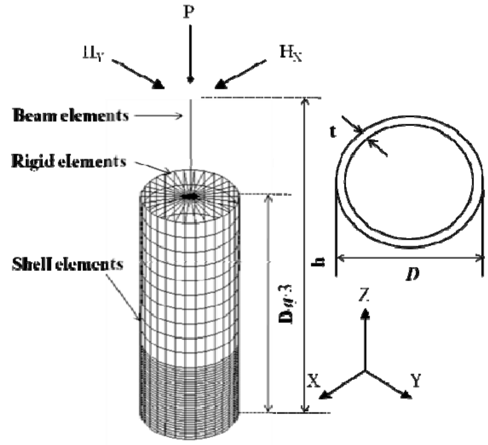

Figure: 2 Analytical model of unstiffened pipe section column

3. Displacement Pattern:

An elliptical displacement pattern as shown in the figure 3 resembling like bi-directional earthquake displacement locus is applied at the apex of the column. *a* and *b* are the lengths of the major and minor axis of ellipse. By taking ratio *b/a* (minor to major axis ratio), 9 patterns are generated like 0(UNI), 0.1, 0.25, 0.5, 0.625, 0.75, 0.9, 0.95, 1(CIR). The numbers of cycles are counted when pattern crosses horizontal axis where X direction displacement becomes negative and Y direction displacement becomes zero.

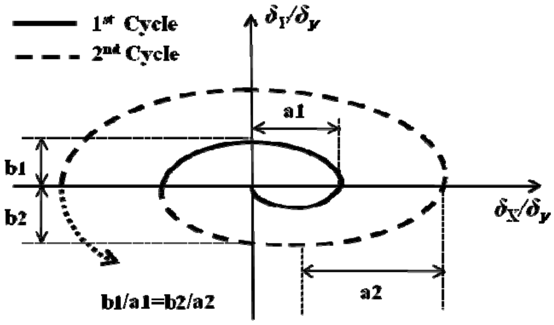

Figure: 3 Definition of cycles and minor to major axis ratio calculation

4. Evaluation of Equivalent Strain, $\bar{\varepsilon}_{ms}$:

With considering local buckling of the pier base, an equivalent strain can be calculated at an effective failure length (L_e=1.2 D (1/$R_t^{0.08}$-1)). The maximum vertical displacement is obtained from the displacements of 30 nodes at the height of L_e. Then equivalent strain is calculated from the formula, $\bar{\varepsilon}_{ms} = \Delta L(t)_{\max}/L_e$.

5. Equivalent strain of model UP100-40:

As for uni-directional loading, ultimate strain ε_u is used for safety verification and is found from average compressive strain at the point of 95% of maximum after peak strength; the same concept is applied for bi-directional loading where strength is calculated by the formula, $H = \sqrt{H_X^2 + H_Y^2}$. The maximum cycle number, $C_{\max}$, maximum equivalent strain, $\bar{\varepsilon}_{ms,\max}$ and equivalent strain at 95% of strength, $\bar{\varepsilon}_{ms,95}$ values are given in the Table 3. The figures 4 and 5 are also plotted for maximum equivalent strain, $\bar{\varepsilon}_{ms,\max}$ versus minor to major axis ratio, *b/a* and equivalent strain at 95% of strength, $\bar{\varepsilon}_{ms,95}$ versus *b/a* ratio respectively.

Table: 1 Structural properties of model UP100-40

R_t	λ	D (mm)	t (mm)	h (mm)	L_e (mm)
0.1	0.40	1560	20	8610	376

Table: 2 SM490 steel material properties

E (GPa)	σ_y (MPa)	ε_y (%)	E_{st} (GPa)	ε_{st} (%)	ν	σ_u (MPa)
200	315	0.157	6.67	1.10	0.3	490

Where, E=Elastic modulus, σ_y =Yield stress, ε_y =Yield strain, E_{st} =Initial hardening modulus, ε_{st} = Initial hardening strain, ν=Poisson's ratio, σ_u =Ultimate stress.

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Table: 3 Maximum number of cycle C_{max} at H_{max}, Maximum equivalent strain, $\varepsilon_{ms,\max}$ and equivalent strain at 95% of strength, $\varepsilon_{ms,95}$ for UP100-40 model

Loading Pattern (b/a)	C_{max}	$\bar{\varepsilon}_{ms,\max}/\varepsilon_y$	$\bar{\varepsilon}_{ms,95}/\varepsilon_y$
0(UNI)	3.00	12.58	20.41
0.1	3.00	13.65	19.43
0.25	3.00	13.74	19.51
0.5	3.00	16.12	21.67
0.625	2.50	8.36	21.63
0.75	2.50	8.32	22.59
0.9	2.50	9.92	22.01
0.95	2.50	6.59	6.74
1.0(CIR)	2.50	8.41	8.03

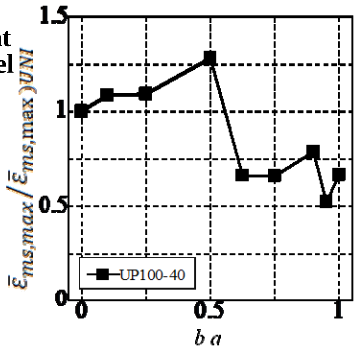


Figure: 1 Maximum equivalent strain, $\varepsilon_{ms,\max}$ versus b/a ratio

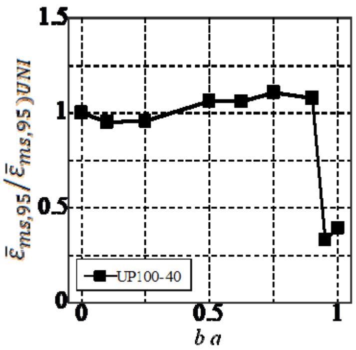
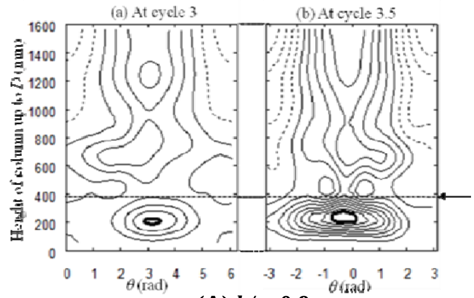


Figure: 2 Equivalent strain at 95% of strength, $\varepsilon_{ms,95}$ versus b/a ratio

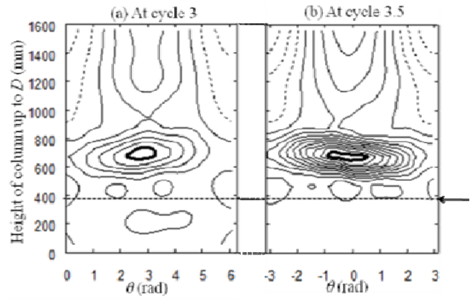
Equivalent strains in both the graphs are made dimensionless by dividing equivalent strain for uni-directional loading (i.e. b/a=0). It can be observed from the graphs that, $\varepsilon_{ms,\max}/\varepsilon_{ms,\max)UNI}$ values are above unity for=0 to 0.5 and then reduced than unity for b/a=0.5 to 1. However, $\varepsilon_{ms,95}/\varepsilon_{ms,95)UNI}$ values are nearly remain constant up to b/a=0.9 and then suddenly reduced for b/a=0.95 and 1(CIR). This means that applicability of $\varepsilon_{ms,95}$ values is safer than $\varepsilon_{ms,\max}$ values for b/a=0 to 0.9. To investigate further, the reason of reduction in the values of $\bar{\varepsilon}_{ms,95}$ at b/a=0.95 and 1(CIR) contour graphs are plotted for deformation outside the surface.

6. Observation of contour graphs:

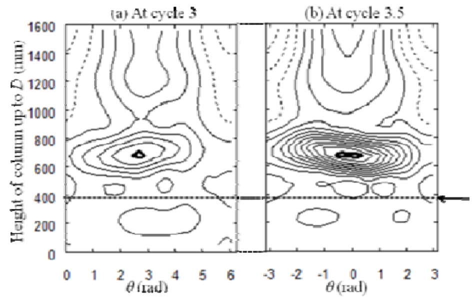
The contour graphs immediately before and immediately after the ultimate strength are plotted for deformation outside the surface of pier, and for b/a=0.9,0.95 and 1(CIR) as shown in the figure 6 (A),(B) and (C). The deformation outside the surface quantities are calculated for each node up to height of first diaphragm interval with the formula, $\delta_d(\bar{t})_i = \sqrt{x(\bar{t})_i^2 + y(\bar{t})_i^2} - r$, where $\delta_d(\bar{t})_i$ is deformation of node i outside the surface after time $\bar{t}$, $x(\bar{t})_i$, $y(\bar{t})_i$, are the coordinates of the node i after time $\bar{t}$ and r is the radius of the circular column. The deformation $\delta_d(\bar{t})_i$ is made dimensionless, dividing by thickness, t of steel pier. In the graphs, angular values of nodes, θ on horizontal axis and height of column up to first diaphragm, D on vertical axis are plotted. The contour line interval is set to 0.25. The dotted lines for negative values, solid thin lines for positive values and solid thick lines for maximum values are plotted respectively. The arrow indicates the effective failure length, L_e. The graphs for b/a=0.95 and 1(CIR) show the maximum deformation occurs above the effective failure length where as for b/a=0.9 it is below L_e, which means that calculation of equivalent strain, at the height of L_e is not feasible for b/a=0.95,1(CIR). The figure 7 shows the relationship between equivalent strain, ε_{ms} and maximum deformation outside the surface, $\delta_{d,\max}$ at each cycle and for all loading pattern. An equivalent strain, ε_{ms} is made dimensionless, dividing by yield strain, ε_y. This graph shows linear relationship between $\bar{\varepsilon}_{ms}$ and $\delta_{d,\max}$ for b/a= 0(UNI) to 0.9, but not for b/a=0.95,1(CIR).



(A) b/a=0.9



(B) b/a=0.95



(C) b/a=1(CIR)

Figure: 6 Contour graphs for model UP100-40

7. Conclusion:

The results obtained from steel circular column UP100-40, it can be concluded that, the method of calculation of ultimate strain (at 95% of strength) for uni-directional earthquake motion can be safely applicable for bi-directional earthquake motions simultaneously, except circular and nearly circular loading patterns (b/a=0.95,1(CIR)). However, it is needed to investigate the suitable effective failure length for viable verification of circular loading pattern and also require carrying out the same analytical study for models having various radius thickness ratio, R_t and slenderness ratio, λ.

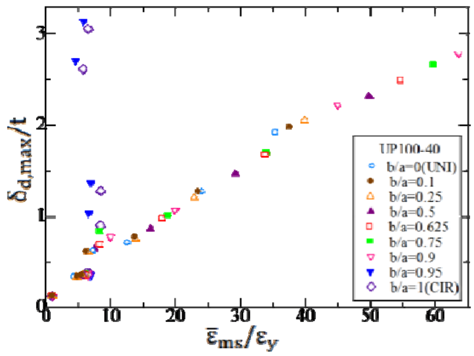


Figure: 7 Relationship between equivalent strain, and maximum deformation outside the surface, $\delta_{d,\max}$

Reference

1) Japan Road Association, "Design Specifications of Highway Bridges", V, 2002 (in Japanese).
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