STRAIN BASED SEISMIC VERIFICATION METHOD FOR THIN-WALLED STEEL CIRCULAR COLUMNS SUBJECTED TO BI-DIRECTIONAL CYCLIC LOADING

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1. Introduction

The thin-walled steel columns are distinctively used for highway bridge piers in Japan, because of rapid construction and smaller section. However, some of the regions of Japan are seismically active and had experienced moderated and severe earthquakes. The effects of past earthquakes on the steel piers showed drawbacks in seismic design methods. Since that, number of researches has been contributed to understand the exact behavior of steel piers under cyclic loading. Hence, initially uni-directional cyclic loading was considered to find out strength and ductility with carrying out experiments and developing special constitutive law for material. Further research found that bi-directional cyclic loading is more destructive than uni-directional loading and actual earthquake also contains more than one component. Particularly for circular steel piers, bi-directional circular cyclic loading[1)] is considered as more rigorous than any other bi-directional loading.

From the literature[2)] it has been proved that seismic verification based on the displacement of top node of column, gives slightly over safe design than strain approach. However, in above mentioned literature formula used for ultimate strain, was developed for combined bending and compression. Hence, the aim of the present study is to evaluate ultimate strain formula and strain based seismic verification method for thin-walled steel circular steel columns.

2. Analytical model and Loading pattern

Two types of FE models are constructed by using ABAQUS program. The first model of column which considers local buckling effect is made up of shell elements in bottom part and beam elements in upper part. Another model is entirely modeled with beam elements (Fig.1a, d). The ring type diaphragms are located at distance D in shell element model (Fig. 1c). With using different combinations of radius thickness ratio $R_t = (\sigma_y / E)(d / 2t)\sqrt{3(1-\upsilon^2)}$, slenderness ratio $\bar{\lambda} = (2h / r\pi)\sqrt{\sigma_y / E}$ and axial force ratio P/P_y=0.15, 12 models are considered in the present study and their geometrical properties are given in Table 1. The in-house developed modified two surface constitutive law is applied to material of shell elements only in case of model shown in Fig. 1a and beam elements of model shown in Fig. 1d. The material properties are given in the Table 2. Both uni and bi-directional circular loading patterns are applied to the top of the columns (Fig. 1b,d).

3. Observations and Results

The FE models are statically analyzed for constant vertical force and uni or bi-directional displacement applied to the top node of the column. The observation of strain is limited to the bottom most height equal to effective failure length, $L_e = 1.2D(1/R_t^{0.08} - 1)$. Hence, in case of shell element model, an equivalent strain is calculated by considering maximum vertical displacement envelop obtained from 30 nodes at the level of L_e and then dividing by L_e (Fig. 2a). Whereas, concerned with beam element model, an average compressive strain is evaluated by taking average of strain histories in each element within effective failure length (Fig 2b).

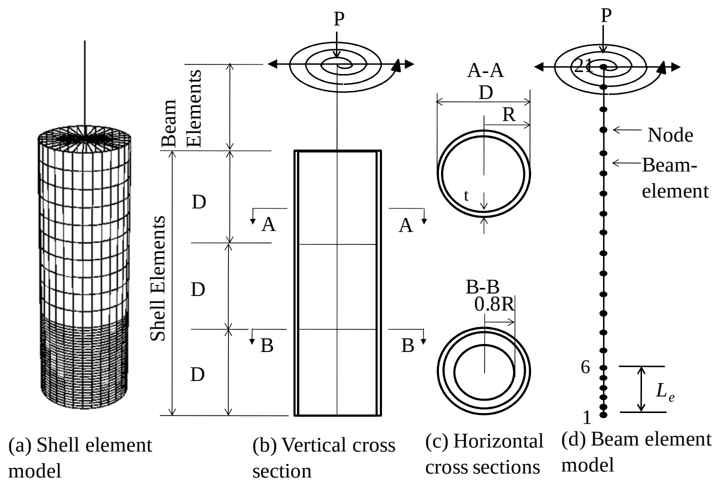

Fig.1 Details of FE models

Table 1. Geometrical properties of column

Column	R_t	$\bar{\lambda}$	D (mm)	H (mm)	t (mm)	L_e (mm)
P50-20	0.050	0.20	789	2152	20	256
P50-40	0.050	0.40	789	4303	20	256
P50-60	0.050	0.60	789	6455	20	256
P60-20	0.060	0.20	942	2582	20	285
P60-40	0.060	0.40	942	5164	20	285
P60-60	0.060	0.60	942	7745	20	285
P75-20	0.075	0.20	1173	3227	20	324
P75-40	0.075	0.40	1173	6454	20	324
P75-60	0.075	0.60	1173	9681	20	324
P90-20	0.090	0.20	1403	3872	20	358
P90-40	0.090	0.40	1403	7744	20	358
P90-60	0.090	0.60	1403	11620	20	358

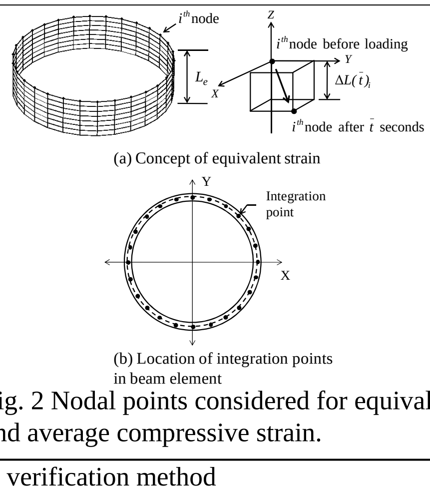

Fig. 2 Nodal points considered for equivalent and average compressive strain.

Table 2. Material properties of SM490 grade steel

E (GPa)	σ_y (MPa)	ε_y (%)	E_{st} (GPa)	ε_{st} (%)	υ	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.

Keyword: circular steel column, ultimate strain, bi-directional loading, seismic verification method
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3.1 Ultimate strain formulas

After carrying out parametric static analysis for both types of models with uni and bi-directional loading, the ultimate strains are observed for corresponding point to 95% of maximum strength on post peak side of strength envelops. Here the restoring strength is calculated by formula $H = \sqrt{H_X^2 + H_Y^2}$. The graph shown in the Fig. 3, indicates the ultimate strains obtained from shell element model $\bar{\varepsilon}_{ms,95}/\varepsilon_y$ and from beam element model $\bar{\varepsilon}_{mb,95}/\varepsilon_y$ for both uni and bi-directional loading with respect to $R_t\bar{\lambda}^{0.2}$. From the graph it can be seen that for short columns ($\bar{\lambda} = 0.2$), circular bi-directional ultimate strains are reduced considerably than uni-directional ultimate strains, hence two separate formulas are proposed here, one for medium-long height columns ($\bar{\lambda} \geq 0.4$) and another for short height columns ($\bar{\lambda} \geq 0.2$) as follows,

$$\frac{\bar{\varepsilon}_{mb,95}}{\varepsilon_y} = \frac{1.28}{R_t\bar{\lambda}^{0.2}} - 5.05 \qquad (\pm 0.52) \qquad (\bar{\lambda} \geq 0.4) \qquad (1)$$

$$\frac{\bar{\varepsilon}_{mb,95}}{\varepsilon_y} = \frac{5.0}{(R_t\bar{\lambda}^{0.2} + 0.4)} \qquad (\pm 0.50) \qquad (\bar{\lambda} < 0.4) \qquad (2)$$

3.2 Strain based seismic verification method

The Fig. 4 shows the procedure developed for seismic verification method when two components of earthquake are applied at the same time. In this method, first two steps are similar to the conventional independent verification method, in which eq. (1) is equally useful for short as well as medium-long columns. In next step column slenderness ratio is checked and maximum strain obtained by bi-directional dynamic analysis is checked with value of eq. (1) if column height is medium-long or with value of eq. (2) if column is short. If the check fails at any step then at first upgradation of column can be preferred and then redesign of the structure option can be considered.

4. Case Study: P75-40:

The model P75-40 dynamically analyzed and verified by using above mentioned method. The Fig. 5 shows the average compressive strain time history observed with in effective failure height L_e. The green line indicates the ultimate displacement limit obtained from bi-directional seismic verification method based on displacement[2]. The blue line is plotted according to the ultimate strain formula[3] for combined bending and compression which is as follows,

$$\frac{\varepsilon_u}{\varepsilon_y} = \frac{0.14(1.1 - P/P_y)^{1.8}}{(R_t - 0.03)^{1.4}} + \frac{3}{(1.1 + P/P_y)^{0.7}} \leq 20.0 \qquad (3)$$

The red line is calculated from the eq. (1) which is derived by considering whole model of column and bi-directional cyclic loading. From this observation it can be supposed that, the column which is unsafe for bi-directional displacement based seismic check and combined bending and compression strain check, give safe performance for bi-directional strain based seismic check.

5. Conclusion

In the present work, attempts are made to derive empirical formulas for ultimate strain and seismic verification method, when thin-walled circular steel columns are subjected to the bi-directional loadings. The observations for short columns shows that, bi-directional ultimate strength and strain are lower than uni-directional respective values hence, the separate formulas are developed for short columns and medium-long columns. The results shown by case study indicate that the present seismic verification method is economical than any other past seismic verification method.

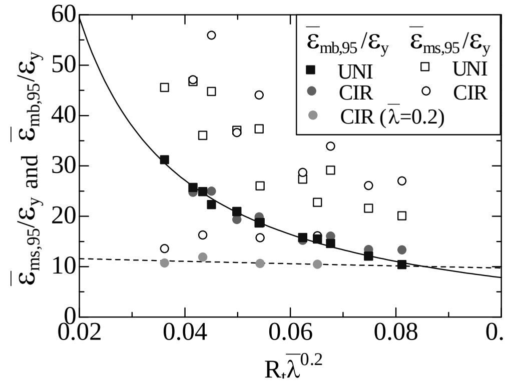

Fig.3 Formulation of ultimate strain

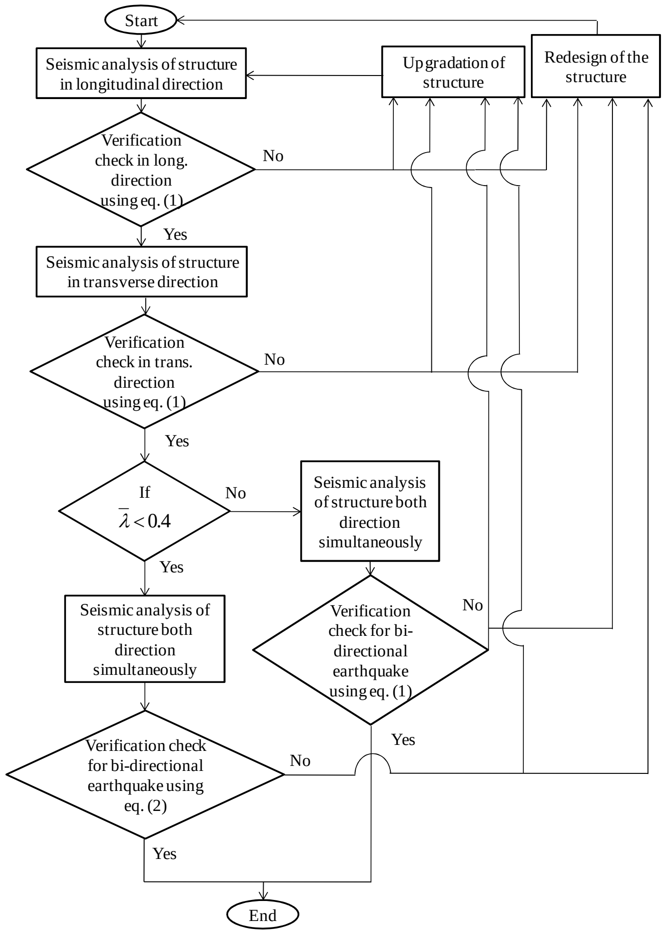

Fig. 4 Bi-directional strain based seismic verification method

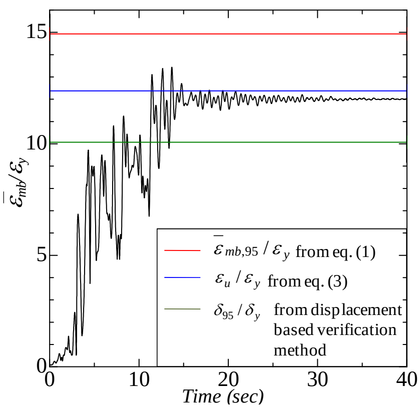

Fig. 5 Average compressive strain history for P75-40

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2) Tsuboi H, Torii J, Kasai A, Usami T. J Structural and Earthquake Engg JSCE, 2007; 29: 529-38 (In Japanese).
3) Ge H, Kono T, Usami T. J Structural and Earthquake Engg JSCE,2004; 50: 1479-88 (In Japanese).