COMPARISON OF SEISMIC PERFORMANCE OF STIFFENED BOX COLUMNS HAVING CONSTANT THICKNESS PLATES AND TAPERED PLATES

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Abstract:
Various methods have been proposed for improving seismic resisting performance of steel columns representing highway bridge piers. One such attractive method is to use linearly tapered steel plates at the critical part of a column because it is economical in terms of steel usage and useful in improving seismic resisting performance. In this study, several important issues related to the comparison of tapered plate columns with equivalent constant thickness plate columns are discussed in view of economical and seismic performance aspects. For comparison purposes an equivalent section is chosen for tapered section by using several constant thickness plate sections which satisfy a given design conditions. Here, the height of the column and axial load capacity are considered to be the key design parameters and are kept constant when designing the equivalent sections. By systematical investigation of influence of the structural parameters, the most suitable constant thickness plate is chosen.

Key words: *ductility, seismic resisting performance, strength, steel columns, tapered plates*

1. Introduction

Steel bridge piers subjected to inelastic deformation usually fail due to extensive damage caused by local buckling of their component plates at the vicinity of the column base. This has been clearly evident from the past earthquakes such as infamous 1995 Kobe Earthquake in Japan. Ever since, numerous experimental and analytical investigations have been conducted aiming at identifying seismic resisting characteristics of steel bridge piers. As a result of these studies seismic design codes have been revised. Furthermore, new design techniques have also been introduced to improve seismic resisting performances of steel bridge piers. The ultimate strength and ductility are the main components of seismic design methodologies where as energy absorption capacity is also increasingly adopted currently. One of an innovative idea on techniques of seismic performance improvement is to use linearly tapered steel plates at the critical part of columns (e.g., Murakami and Nishimura 1996, Miki and Kawada 2000, Ekeuchi *et al*. 2001, Fukumoto *et al*. 2003).

In an early work by Brozzetti (1996), it was found that the cost reduction in material can be achieved by using tapered plate members. However, the benefit cost reduction might be compensated by the additional cost involved in fabrication of steel plates. Murakami and Nishimura (1997) carried out ultimate strength analysis of tapered plate using elasto-plastic finite element analysis procedure. They used equivalent thickness of tapered plate to evaluate the ultimate strength of columns. Miki and Kawada (2000) found that the tapered members cause delayed local buckling, lesser damage than the constant thickness cross-section members and increased energy dissipation. An analytical investigation on earthquake resisting performance of tapered plate bridge piers has been carried out by Ikeuchi *et al*. (2001). According to their results, the stiffener's stiffness ratio of 3.0 was found to offer better ductility than the lower ratios such 1.0. They also revealed from the dynamic response analysis that the maximum and residual displacement demands can be reduced using tapered plates. An experimental work by Fukumoto *et al*. (2003) explained cyclic performance of stiffened square box columns with tapered flange and web plates. The main aim of their study was to investigate the spreading of yielding zones in box columns that facilitates the eliminating of sudden curvature changes along the column. With the spreading of yielding zone severe localized structural failures such as local buckling and material yielding are not likely to occur, hence, the ductility capacity increases. They investigated the effect of tapering ratio on yielding patterns and the number of locally buckled panels. They have found that the tapered plate columns have better performances than constant thickness plate column of the same weight. Fukumoto *et al*. (2005) conducted analytical study on the application of tapered steel plates in rigid-framed steel portal frames for improved seismic resisting performances. Aoki *et al*. (2008) conducted same type of study using experimental means and they revealed that the optimum tapering ratio leads to larger spread of yield zones with less strain concentration.

The main aim of this study is to discuss the advantages of tapered plate columns over equivalent constant thickness plate columns. The equivalent constant thickness plate column is chosen in such a way that both the tapered plate and constant thickness plate columns will have the same load carrying capacities. For a given height and axial load, several sections are designed by varying the geometrical parameters and the most suitable constant thickness plate section, or so called equivalent section, is chosen in view of seismic resisting expected performances.

2. Design parameters of stiffened steel box columns

For the comparison of seismic resisting performance of tapered and constant thickness plate columns, attention should be paid to select suitable equivalent constant thickness plate columns. When equivalent section is chosen, it is considered in this study that the height of the equivalent section column is equal to that of the tapered plate column. In addition, both columns will have the same axial load carrying capacity. This is done by changing geometrical parameters so that the values of important structural parameters in seismic designing of steel rectangular columns will satisfy the specified requirements. The important structural parameters used in JRA (1996) requirements for the design of stiffened steel rectangular columns are flange plate slenderness parameter (R_R), stiffened plate slenderness parameter (R_F), relative flexural rigidity parameter of stiffener (γ_l), optimum rigidity parameter of stiffener (γ_l^*), and slenderness ratio parameter of column ($\bar{\lambda}$). Flange plate slenderness parameter (R_R) and stiffened plate slenderness parameter (R_F) are defined by (Chen and Duan, 2000).

$$R_R = \frac{b}{t}\sqrt{\frac{\sigma_y}{E}\cdot\frac{12(1-\nu^2)}{\pi^2 k_R}}\ ;\ R_F = \frac{b}{t}\sqrt{\frac{\sigma_y}{E}\cdot\frac{12(1-\nu^2)}{\pi^2 k_F}} \qquad (1)$$

where b=plate width, t=plate thickness, σ_y=yield stress, E=Young's Modulus, ν=Poisson's ratio, k_R and k_F=buckling coefficients of simply supported plate and stiffened plate, respectively. Relative flexural rigidity parameter (γ_l) of stiffener is give by

$$\gamma_l = \frac{12(1-\nu^2)I_l}{bt^3} \tag{2}$$

where I_l is moment of inertia of the T-section consisting of a longitudinal stiffener and the effective width of the plate to which it connects. The expression for optimum rigidity of stiffeners (γ_l^*) is given by

$$\gamma_l^* = 4\alpha^2 n(1+n\delta_l) - \frac{(\alpha^2+1)^2}{n} \quad \text{for } \alpha \le \alpha_0 \tag{3}$$

$$\gamma_l^* = \frac{1}{n}\left\{[2n^2(1+n\delta_l)-1]^2 - 1\right\} \quad \text{for } \alpha > \alpha_0 \tag{4}$$

where n=number of sub panels in a stiffened plate, δ_l=area ratio of a longitudinal stiffener to plate, α (=a/b)=aspect ratio, a being the spacing between diaphragms. Critical aspect ratio, α_0 is given by

$$\alpha_0 = \sqrt[4]{1+n\gamma_l} \tag{5}$$

In addition, slenderness ratio parameter $\bar{\lambda}$, which plays an important role in overall instability of a column, has been defined by (Ge *et al*., 2000)

$$\bar{\lambda} = \frac{2h}{r}\frac{1}{\pi}\sqrt{\frac{\sigma_y}{E}} \tag{6}$$

where h=column height and r=radius of gyration of cross section. The influence of these parameters on the behavior of steel columns has been discussed in the several past studies (e.g., Usami *et al*., 2000, Ge *et al*., 2000).

3. Design of tapered and constant thickness steel plate columns

A square-shaped stiffened steel column having cross section of 600 mm width and column height of 3000 mm is designed so that first two panels from the bottom will consist of linearly tapered plates. Total height is divided into five panels at equal height (i.e., each panel is 600 mm high). Thickness of tapered plate is chosen to be 8.4 mm at the base and 4.5 mm at the level of the second diaphragm. The rest of the column has steel plates with constant thickness of 4.5 mm. The geometrical details of the column are shown in Figure 1. The design axial load (P) and horizontal yield load (H_y) of tapered plate column are 1590 kN and 477 kN, respectively. For the comparison purposes, six constant thickness plate columns having different thickness are designed. Both the tapered and constant thickness plate columns consist of steel grade SM490 of Japanese Standard (yield stress, σ_y=325 MPa). They are designed to withstand the same axial load (P=1590 kN) and yield load (H_y=477 kN). The height (h) and γ/γ^* ratio of all the columns are kept constant. In addition, the thickness ratio of stiffener to component plate (t_s/t) is kept constant at a value of 1.5. Three (3) ribs are provided at each side of the section in all the columns. All these conditions are maintained by adjusting the width of the section (B) and the length of stiffeners (B_s). The value of H_y is equivalent to 0.3 times the axial load (i.e., H_y=0.3P). In the design tapered plate column, the dimension of the section is chosen to be 600 x 600 mm. Then, in order to have the γ/γ^* ratio at 2.50 and H_y at 0.3P, the value of B_s is decided by following an iterative procedure. Similar procedure is adopted to decide the dimensions of B and B_s of the constant thickness plate columns. For thickness varying from 9 mm to 4.5 mm, the values of dimension B are obtained in the range of 559 mm to 895 mm. The values of important geometrical and structural parameters obtained in the design are shown in Tables 1 and 2, respectively.

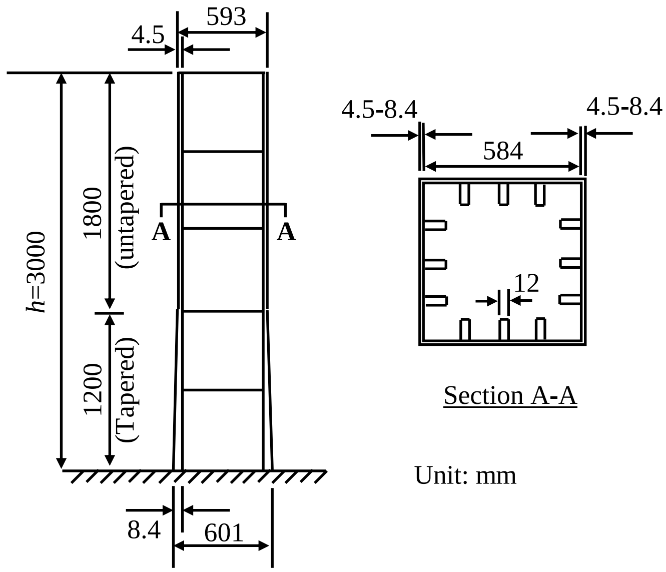

Figure 1. Dimensions of tapered plate steel column

Table 1. Values of geometrical parameters of columns

t (mm)	h (mm)	B (mm)	Bs (mm)	t_s (mm)	t_s/t	A (cm^2)	I (mm^4)
9.0	3000	559	84.3	13.50	1.5	335	1.44×10^9
8.0	3000	605	78.0	12.00	1.5	304	1.59×10^9
7.0	3000	663	71.9	10.50	1.5	274	1.78×10^9
6.0	3000	737	65.5	9.00	1.5	246	2.02×10^9
5.0	3000	834	58.8	7.50	1.5	219	2.36×10^9
4.5	3000	895	55.4	6.75	1.5	205	2.58×10^9
4.5-8.4	3000	598	72.3	12.00	1.6	229	1.44×10^9

Table 2. Values of structural parameters of columns

t (mm)	γ/γ^*	R_F	R_R	P/P_y	λ	P_y (kN)	P (kN)	H_y (kN)
9.0	2.50	0.20	0.31	0.15	0.36	10874	1590	477
8.0	2.52	0.25	0.39	0.16	0.33	9864	1590	477
7.0	2.51	0.31	0.48	0.18	0.30	9814	1590	477
6.0	2.50	0.40	0.63	0.20	0.26	7998	1590	477
5.0	2.50	0.55	0.86	0.22	0.23	7110	1590	477
4.5	2.50	0.66	1.25	0.24	0.21	6670	1590	477
4.5-8.4	2.50	0.26	0.41	0.18	0.33	9085	1590	477

4. Comparisons between tapered plate columns and constant thickness plate columns

4.1 Effects of cross sectional area (*A*) and parameters R_F and R_R

The equivalent constant thickness column can be based on either the same weight of the column or the same structural performance provided that the same design loads are considered in both cases. This can be examined by plotting the cross sectional area (*A*) and parameters R_F and R_R against the thickness of constant thickness columns as shown in Figure 2. The values of *A* (229 mm^2) and R_F (=0.26) of tapered plate column are also marked on the same figure using dashed lines. It is clear from Figure 2 that if *A* is considered to be the basis for deciding thickness of equivalent constant thickness plate column, the value will be around 5.4 mm. On the other hand, if R_F is considered, it is around 7.8 mm. The values of R_F and R_R corresponding to t =5.4 mm are around 0.54 and 0.88, respectively. These values are approximately twice of those of the tapered plate column. The parameter R_F has a significant effect on the ultimate strength and ductility of columns, and the recommended limit is below 0.3 (JRA, 1996). This means that the performance of tapered plate column will be better than that of the constant thickness plate column having thickness of 5.4 mm even though both will be able to withstand the same axial load. Therefore, we need to consider not only the economical aspects such as the weight of the column but also the expected seismic resisting performances. The equivalent section based on parameter R_F (i.e., plate thickness 7.8 mm) would become a reasonable option although it is not an economical section.

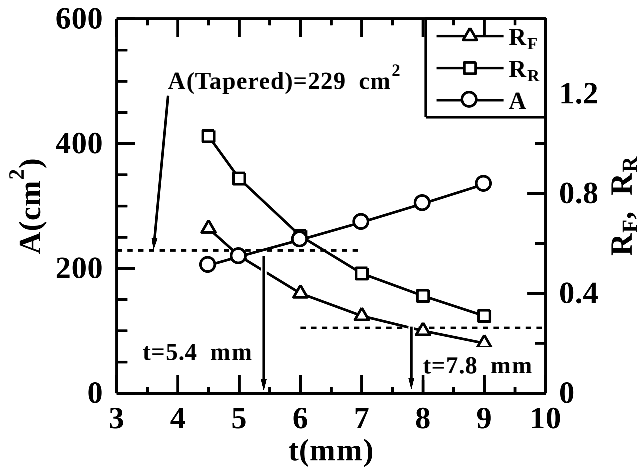

Figure 2 Variations of *A*, R_F, R_R with thickness of plates

4.2 Effects of number of ribs (*N*)

In order to check the effects of number of ribs several columns having a number of ribs from one to seven were designed while maintaining the same design conditions as described in section 4.1. (i.e., h=3000 mm; t_s=1.5$\times t$; γ/γ^*=2.5; P=1590 kN; and H_y=477 kN). The columns consist of three different plate thicknessess (i.e., t = 8.0, 6.0, and 4.5 mm), as given in Table 3. The variation of cross sectional area (*A*), parameters R_F, and R_R with the number of ribs are illustrated in Figure 3. Here, the solid lines correspond to *A* while dashed lines represent parameters R_F, and R_R. It is clear that the cross sectional area (*A*) and the values of parameters

R_F and R_R show an opposite trend with number of ribs. This means that for an economical section (i.e., smaller cross sectional area) number of ribs (N) should be decreased. Contrarily, for better performances (i.e., lower values of R_F and R_R) the number of ribs (N) should be increased. Theoretically, the value at the intersection of two lines corresponding to A and R_F of a particular thickness should give the optimum value of N provided that the limit of R_F lies within the recommended range.

Table 3. Values of parameters for different numbers of ribs

No of Ribs	t (mm)	B (mm)	B_s (mm)	A (cm^2)	γ/γ^*	R_F	R_R	P/P_y	λ
4	8	554	88.2	344	2.51	0.18	0.28	0.14	0.37
3	8	605	78.0	304	2.50	0.25	0.38	0.16	0.33
2	8	657	67.3	272	2.50	0.36	0.56	0.18	0.30
1	8	704	54.0	249	2.50	0.61	0.90	0.20	0.27
5	6	632	80.4	295	2.50	0.23	0.36	0.17	0.32
4	6	684	73.2	268	2.51	0.30	0.47	0.18	0.29
3	6	737	65.5	246	2.50	0.40	0.63	0.20	0.26
2	6	787	57.0	228	2.49	0.58	0.90	0.21	0.24
7	4.5	690	78.0	271	2.51	0.25	0.40	0.18	0.29
6	4.5	741	72.5	250	2.50	0.31	0.49	0.20	0.27
5	4.5	793	67.0	232	2.50	0.39	0.61	0.21	0.25
4	4.5	845	61.4	218	2.49	0.50	0.78	0.23	0.23
3	4.5	895	55.4	205	2.50	0.66	1.03	0.24	0.21

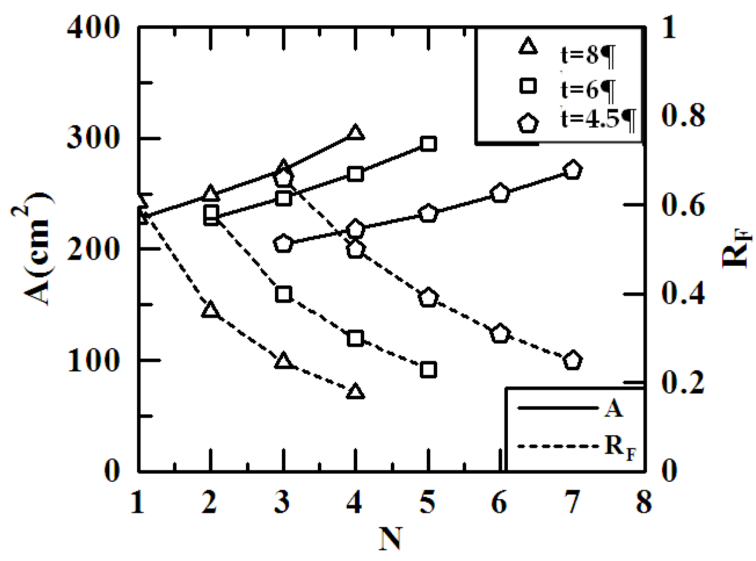

Figure 3. Variations of A and R_F with number of ribs, N

4.3 Combined effects of plate thickness (t) and number of ribs (N)

Several sections with thickness varying from 4.5 to 9.0 mm are designed by adjusting the number of ribs so that the value of R_F is less than or equal to 0.30. The dimensions and values of structural parameters of sections are listed in Table 4. A graphical illustration of relationships of t and N with R_F and R_R, is shown in Figure 4. The value of R_F (=0.262) of the tapered plate column is marked by a dashed line in the same figure. The range of t and N of the constant thickness plate section having the value of R_F less than or equal to 0.262 can be decided using this figure. Here, section with 6 ribs and thickness of around 5.0 mm (N=6, t=5.0 mm) and the one with 3 ribs and thickness of around 8.0 mm (N=3, t=8.0 mm) are found to be the range of appropriate sections.

Table 4. Values of parameters for different numbers of ribs for Rf$\leq$0.30

No of Ribs	t (mm)	B (mm)	B_s (mm)	A (cm^2)	γ/γ^*	R_F	R_R	P/P_y	λ
6	4.5	741	72.5	250	2.50	0.31	0.49	0.20	0.27
6	5.0	678	77.7	275	2.51	0.25	0.40	0.18	0.30
5	6.0	632	80.4	296	2.50	0.23	0.36	0.17	0.32
4	7.0	610	80.6	304	2.50	0.23	0.36	0.16	0.33
3	8.0	605	78.0	304	2.50	0.25	0.39	0.16	0.33
2	9.0	610	72.2	295	2.50	0.30	0.46	0.17	0.32

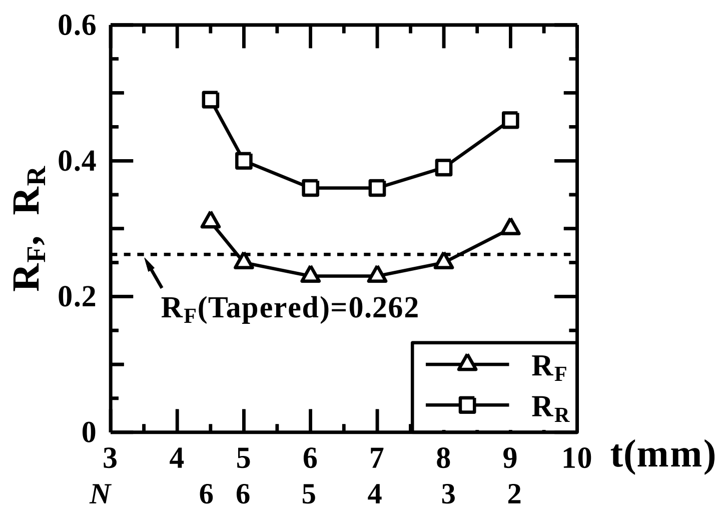

Figure 4. Relationship of t and N with R_F and R_R

4.4 Influence of slenderness ratio parameter (λ) on selection of equivalent section

The variation of column slenderness parameter along with different sections is plotted in Figure 5. The value corresponds to tapered plate column is marked by a dashed line in the same figure. The values of λ in all the constant thickness columns are either equal or less than that of tapered plate column. Therefore, the influence of λ in selecting the equivalent section column can be neglected since all the constant thickness plate columns are in the safe side with respect to the slenderness of columns.

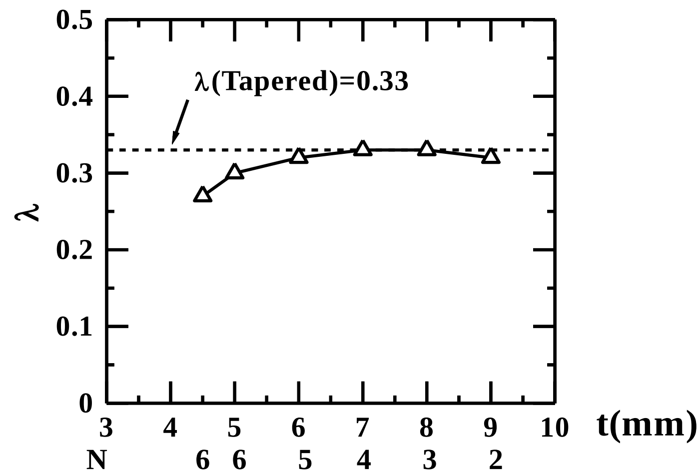

Figure 5. Relationship of t and N with λ

5. Conclusions

This paper discussed the influence of important structural parameters in comparison of tapered plate columns with equivalent constant thickness plate columns. A systematic analysis of the effects of sectional dimension on the value of each structural parameter was done to this end. It was understood from the analyses that the cross sectional area (A) alone is not a reasonable option in deciding the equivalent section. The equivalent section should be decided considering the most influential parameters on the seismic resisting performance. Stiffened plate slenderness parameter (R_F) was identified as one of the most suitable basis for this purpose. The number of ribs (N) is another important parameter and the optimum value of N should be decided based on combined effect of cross sectional area and the stiffened plate slenderness parameter. Once the equivalent section is chosen, appropriate analysis should be conducted to verify the actual performance of tapered and equivalent columns. Pushover analysis, lateral cyclic load analysis and/or dynamic time series analysis can be conducted as an extension work of this study.

References

Aoki, T., Takaku, T., Fukumoto, Y, and Susantha K.A.S., "Experimental investigation for seismic performance of framed structures having longitudinally profiled plates" *Journal of Constructional Steel Research*, 2008, 64, 875-881.

Brozzetti, J.B., “Recent developments in composite bridges” *Proc. 3rd International Symposium on Steel Bridges*, Rotterdam, 1996, ECCS, S1 8-18.

Chen, W. F. and Duan, L., Bridge Engineering Handbook, CRC Press, 2000, Boca Raton, FL.

Fukumoto, Y., Uenoya, M., Nakamura, M., and Saya, H., “Cyclic performance of stiffened square box columns with thickness tapered plates” *Journal of Steel and Structures*, 2003;3(2):107–15.

Fukumoto Y, Takaku T, Aoki T. and Susantha K.A.S.,” Innovative use of profiled steel plates for seismic structural performance” *Journal of Advances in Structural Engineering* 2005;8(3):247–57.

Ge, H. B., Gao, S. B. and Usami, T., “Stiffened steel box columns. Part 1: Cyclic behavior” *Earthquake Engineering and Structural Dynamics*, 2000, 29, 1691-1706.

Ikeuchi, T., Nose, M., Nishimura, N., and Takagi, M. (2001). “Improvement of earthquake resistance performance of steel bridge piers using tapered plate.” 1st International Conference on Steel & Composite Structures, Pusan, Korea, 1557-1564.

JRA, Specification of Highway Bridges, Japan Road Association, Tokyo, Japan, 1996.

Miki, T. and Kawada, S., “An experimental study on the elasto-plastic hysteretic behavior of partially tapered steel beam-columns.” *J. Structural Mechanics and. Earthquake Engineering*, JSCE, 2000, Vol. 647, No. I-51, 345-355 (in Japanese).

Murakami, S. and Nishimura, N., “Ultimate strength evaluation of tapered plate in compression” *Proc. 5th International Colloquium on Stability and Ductility of Steel Structures*, Nagoya, 1997, 133-140.

Usami, T., Gao, S. and Ge, H., “Stiffened steel box columns. Part 2: Ductility evaluation” *Earthquake Engineering and Structural Dynamics*, 2000, 29, 1707-1722.