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Local Buckling of Concrete Filled Steel Square Tubular Columns

Voilement local de colonnes mixtes en tubes carrés remplis de béton

Örtliche Beulen von betongefüllten, quadratischen Hohlprofilstützen

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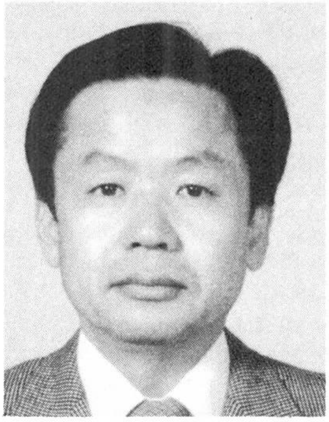

Chiaki Matsui, born 1937, graduated from the Department of Architecture, Kyoto University in 1962, received a doctorate in engineering at Kyoto University in 1971. He has worked at Kyushu University since 1968 and has been a professor since 1980. His researches have been concerned with strength and behaviour of steel and composite structures.

SUMMARY

This paper presents a new limiting value of the width-to-thickness ratio for plate elements of concrete filled steel square tubular columns. The new value is derived from the comparison of the post buckling behavior of concrete filled tubular members with that of hollow tubular members from the viewpoint of equivalent energy absorption capacity. The post buckling behavior is obtained on the basis of plastic limit analysis for collapse mechanisms due to local buckling of tubes. The proposed value is about 1.5 times of that currently used for steel structures.

RÉSUMÉ

Cet article présente une nouvelle valeur du rapport épaisseur/largeur des faces des colonnes formées de tubes carrés remplis de béton. Cette nouvelle valeur est tirée de la comparaison entre le comportement au voilement des tubes creux et celui de ces mêmes tubes remplis de béton, en considérant l'énergie d'absorption. Le comportement post-critique est obtenu en analysant le mécanisme plastique du voilement local des tubes. La valeur proposée est d'environ 1,5 fois supérieure à celle utilisée couramment en construction métallique.

ZUSAMMENFASSUNG

Dieser Beitrag beschreibt einen neuen begrenzenden Wert des Breite/Dicke-Verhältnisses von Plattenelementen bei betongefüllten, quadratischen Hohlprofilstützen. Der neue Wert wird abgeleitet aus dem Vergleich des Beulverhaltens im überkritischen Bereich von betongefüllten Hohlprofilelementen mit demjenigen von Hohlprofilelementen unter dem Gesichtspunkt eines gleichwertigen Energieaufnahme-Vermögens. Das Beulverhalten im überkritischen Bereich, auf der Basis einer plastischen Grenzanalyse für den Bruchmechanismus, verursacht durch ein örtliches Beulen der Hohlprofile. Der vorgeschlagene Wert ist ungefähr 1,5fach grösser als der gegenwärtig bei Stahlbauten angewandte.

1. INTRODUCTION

Strength and behavior of concrete filled steel tubular members have been investigated in Europe, U.S.A. and Japan, and it becomes known that there are many advantages to be gained by combining the properties of steel hollow sections with those of concrete to form a composite column. It is recognized that the load carrying capacity and deformation capacity of these columns are both satisfactory in comparison with those of steel tubular columns or ordinaly reinforced concrete columns.

However, in the design of concrete filled tubular columns, the limiting width-to-thickness ratio of plate elements of a composite column is usually used with the same value as for hollow sections. The ratio is about 50 for mild steel square tubes based on the allowable stress design method in Japan. Other countries have basically adopted the same values. It seems too conservative for concrete filled tubular columns.

This paper presents the results of analyses for plastic collapse mechanisms of tubular columns filled with and without concrete and gives a new limiting value. This value is derived from the comparison of the post buckling behaviors of concrete filled tubular members with those of hollow tubular members from the viewpoint of equivalent energy absorption capacity of the members. The proposed value is about 1.5 times of that currently used for steel structures. This conclusion enables us to construct ductile and low cost building frames by using concrete filled steel tubular columns.

2. EFFECT OF FILLED CONCRETE

The effect of filled concrete on the behavior of frames with steel square tubular columns is discussed. Figure 1 shows the behavior of two frames under constant vertical and varying horizontal loads [1]. Frame A is composed of hollow tubular columns and Frame B is composed of concrete filled tubular columns. The same steel tubular columns and wide flange beams in size and property are used for two frames. The width-to-thickness ratio B/t of the tube is about 47. The limiting value specified in the AIJ design standard for steel structures [2] is $d/t \leq 232/\sqrt{F}$ for square and rectangular tubes of uniform thickness (Fig. 2). Where F is defined as the basic value used in determining allowable stresses and the specified minimum yield point 23.5 KN/cm^2 ($t \leq 40$ mm) is used for mild steel. Using the actual yield stress of the tubes 32.4 KN/cm^2 instead of the specified value, d/t becomes about 41. The radius of the section corner r is nearly equal to plate thickness t, then the limiting value B/t for the tubes becomes 45. The ratio of the tubes is a little over the limiting one. The beam-to-column connections of the frames are designed in order to have enough strength to transfer the stresses from the beams to the columns.

The restoring force of Frame A decreases rather rapidly at the occurrence of web local buckling after flange local buckling of the tubes. However, when the tubes are filled with concrete, the restoring force is strengthened due to the concrete and the behavior is markedly improved, especially in the post local buckling range. The main reasons for the improvement in post buckling behavior are as follows:

1° Collapse mechanism of a concrete filled tube due to local buckling is different from that of a hollow tube.
2° In concrete filled tubes, a part of or all of compression force sustained by the tube can be transfered to the concrete after the occurrence of local buckling.

The reason 1° will be mentioned in the next section in reference to the analyses for post buckling behavior of tubes.

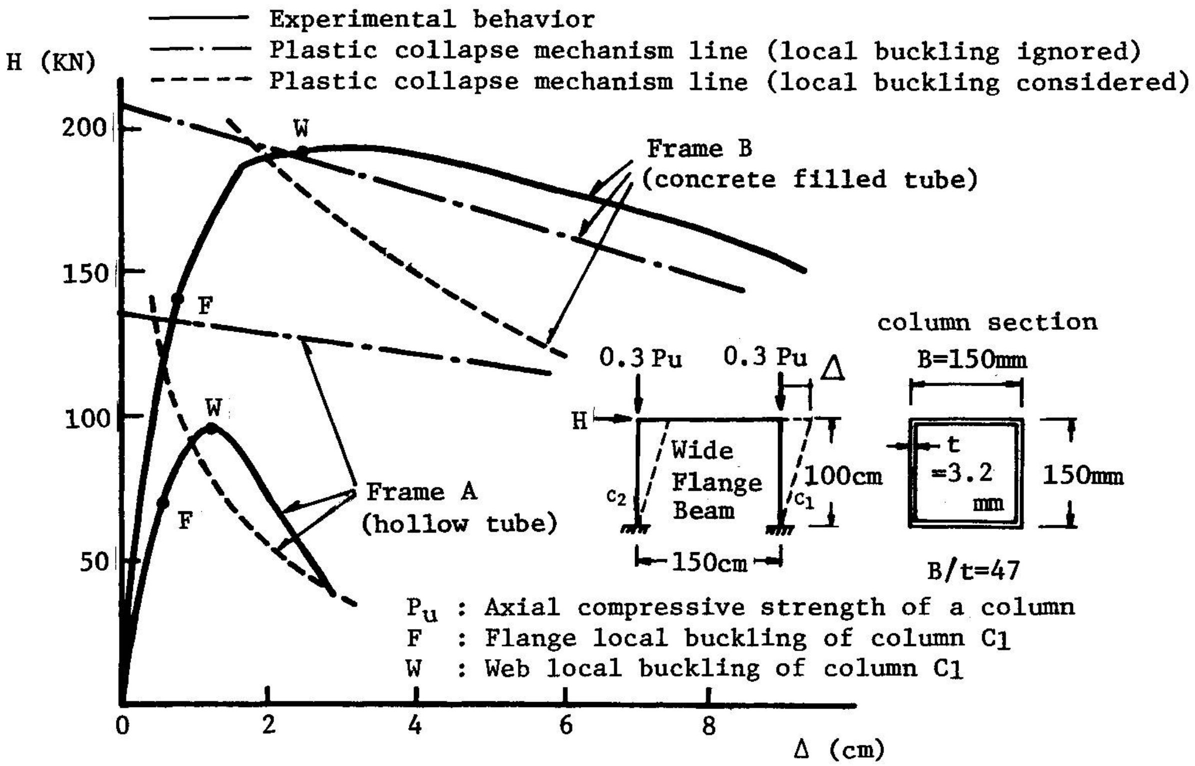

Fig. 1 Behavior of Frames

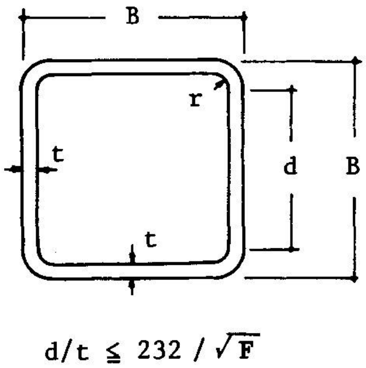

Fig. 2 Shape of Tube

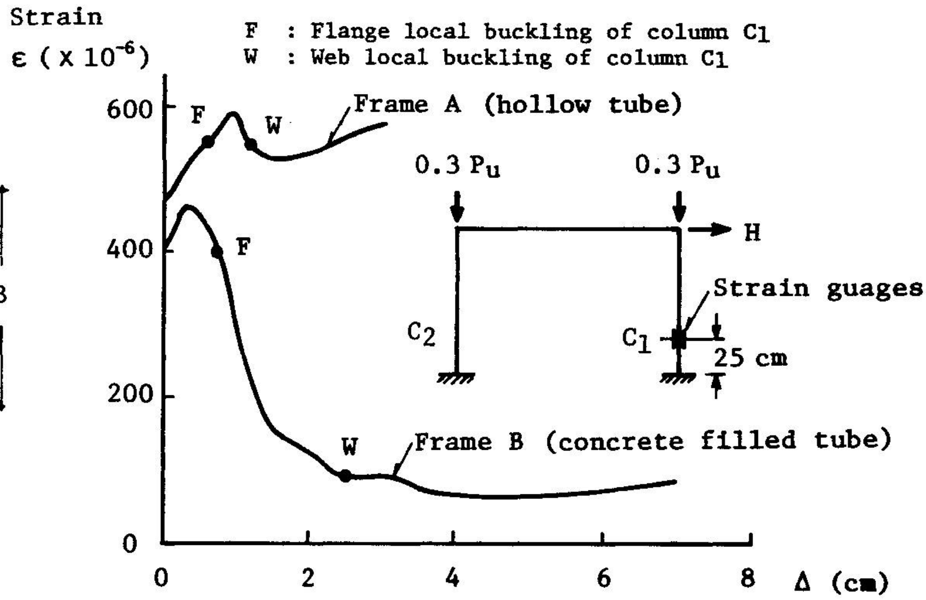

Fig. 3 Change of Average Compressive Strain in Steel Tube

Figure 3 shows an example of supporting bases for 2°. It represents the relationship between average compressive strain of the tube and sidesway displacement of the frame. The strains were measured by two strain gauges at points 25 cm apart from the column end. In Frame B, rapid reduction in strain is observed after the occurrence of local buckling near the column end. From this figure, it is recognized that when the axial rigidity of a tube decreases as a result of the appearance of local buckling in the tube, the compressive force in the tube transfers to the concrete under the condition of constant column axial load.

3. ALLOWABLE COMPRESSIVE LOAD ON A COMPOSITE COLUMN

In the case that the value of constant compressive axial load applied to a composite column exceeds the maximum compressive strength of the concrete, the steel tube must sustain a part of it. The compressive load which a tube must sustain can be obtained from the following manner. In the design of composite columns, allowable compressive load P is recommended in the AIJ standard for Structural Calculation for Steel Reinforced Concrete Structures [3] as follow:

$$P \leq \frac{1}{3}\cdot {}_cA\cdot F_c + \frac{2}{3}\cdot {}_sA\cdot \sigma_y \tag{1}$$

where ${}_cA$ and ${}_sA$ are areas of concrete and steel, respectively, F_c compressive strength of concrete and σ_y yield stress of steel. Eq. (1) has been proposed on the basis of the experimental data and it guarantees for a column the deformation capacity of 0.01 rotation angle under cyclic plastic bending moment. It is assumed that the compressive strength of the concrete is equal to ${}_cA\cdot F_c$ and the compressive load P' which a tube must sustain is expressed as $P' = P - {}_cA\cdot F_c$. By substituting Eq. (1) for the equation of P' and expressing yield load of a tube $P_y = {}_sA\cdot\sigma_y$, the following equation can be obtained.

$$\frac{P'}{P_y} = \frac{2}{3}\cdot\left\{1 - \frac{F_c}{4\sigma_y}\cdot\frac{(B/t-2)^2}{(B/t-1)}\right\} \tag{2}$$

Figure 4 shows Eq. (2) for three values of a parameter σ_y/F_c which cover the ordinary range of material strengths. From this figure, it is recognized that a tube does not need to sustain compressive force after the occurrence of local buckling under the condition of B/t > 50. In this case all compressive load sustained by a tube is able to be transfered to the concrete.

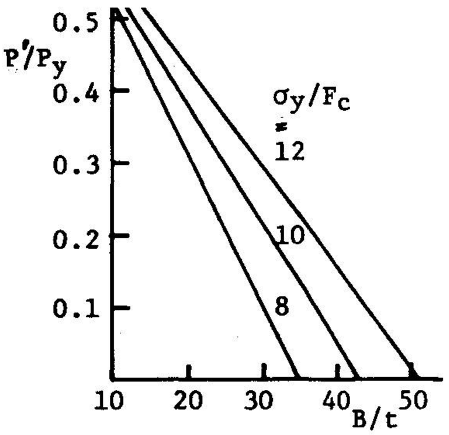

Fig. 4 Axial Force of Steel Tube

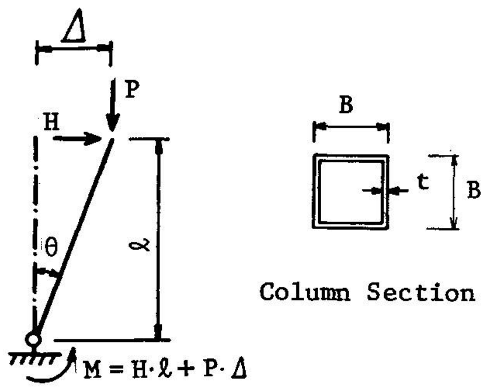

Fig. 5 Analytical Model of a Column

4. PLASTIC COLLAPSE MECHANISM DUE TO LOCAL BUCKLING

The post buckling behavior of steel hollow square tubular columns has been investigated on the base of plastic limit analysis [4]. The same technique can be applied to the analysis for tubes filled with concrete. The deformed configuration of a cantilever column at the post local buckling state is idealized as shown in Fig. 5. The local buckling mechanism is assumed as shown in Fig. 6.

The buckling mode of a tube filled with concrete differs from that of a hollow tube (Fig. 6(d)). In the case of a concrete filled tube, plate elements deform only outside of a section and plastic hinge lines form at the edges of the compression flange as shown in Figs. 6(a), (b), (c). $M-\theta$ relation of a model can be obtained by applying the principle of virtual velocities, and it can be written as follows:

$$M = -P\cdot(\eta - 0.5)\cdot d + D_p / \dot{\theta} \tag{3}$$

where M denotes the applied moment at the plastic hinge, P the constant vertical load, ηd the distance between compressive flange and neutral axis, d the web depth, $\dot{\theta}$ the virtual angular velocity of the plastic hinge, and D_p the rate of internal energy dissipation. The prime assumptions to estimate the value of D_p are as follows, 1) plate elements are in state of the plane stresses, 2) the material has a rigid-perfectly-plastic characteristic conforming to the yield condition of von Mises. 3) Plastic axial deformation at hinge lines is ignored. 4) Effect of shear force is ignored. The value of D_p is dependent on 3 variables ψ, η and θ (see Figs. 6(a), (b)) that define the form of the local buckling mechanism, and therefore the resisting moment M in Eq. (3) is also dependent on them. Based on the plastic upper bound theorem, the minimum resisting moment among the values computed by Eq. (3) gives a correct solution. Minimum moment is obtained by changing the values of η, ψ for a given value of θ.

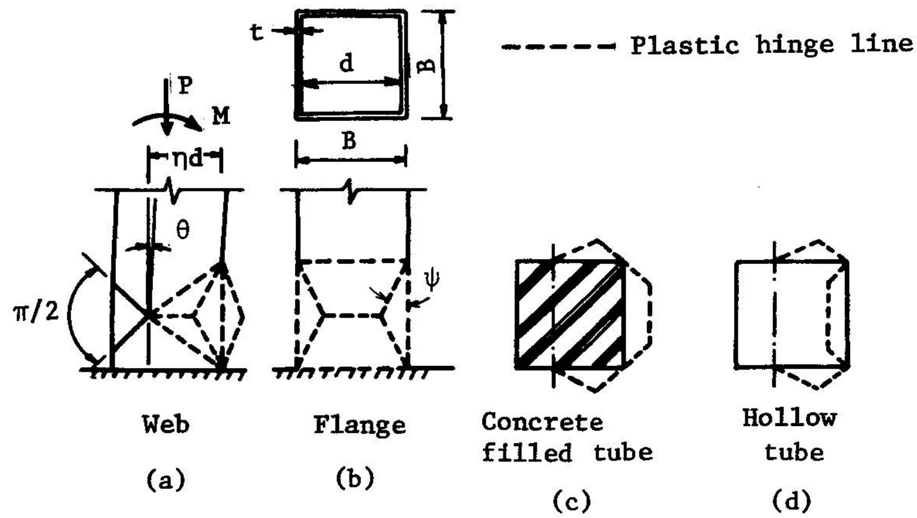

Fig. 6 Collapse Mechanism due to Local Buckling

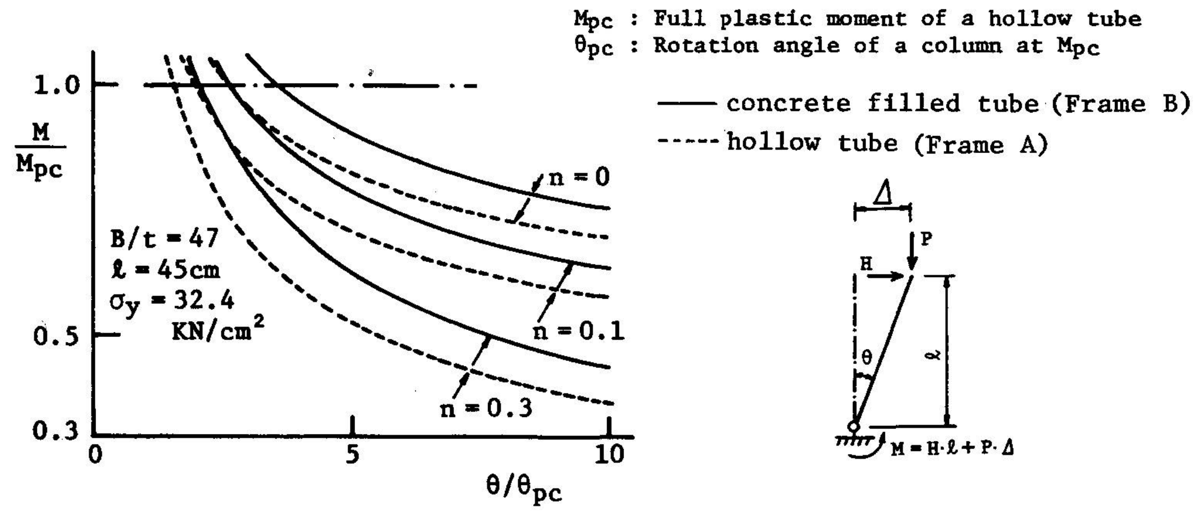

Fig. 7 Post Buckling Behavior of Columns

Figure 7 shows the numerical results for the columns of the frames shown in Fig. 1. The columns are analyzed as a cantilever of 45 cm in length which represents the distance from the inflection point of a column at the collapse mechanism state to the end of the column. There are no remarkable differences in the behavior of two columns having the same axial load ratio n. However, in the case of Frame B, the compressive load in a tube is transfered to the concrete after the occurrence of local buckling. Then, the behavior of a concrete filled column of $n = 0$ should be compared with that of a hollow column of $n \neq 0$. It is recognized that there are remarkable differences in the behavior of the two columns. By using the numerical results, the plastic collapse mechanism lines considered local buckling for two frames are shown in Fig. 1. In the mechanism line of Frame B, the ultimate bending strength of the concrete is calculated under the assumption that compressive stress distribution is rectangular with the constant value of compressive strength F_c and all of the vertical load P is applied to the concrete. The bending strength of a composite column is assumed to be expressed by the superposition of the strengthof the tube and the conrete.

5. LIMITING VALUE OF WIDTH-TO-THICKNESS RATIO

Based on the above mentioned considerations, a new limiting value of width-to-thickness ratio for concrete filled steel square tube columns can be derived in the following manner. First, a hollow tube with $B/t = 50$ is selected as a standard member made of mild steel in strength and behavior. $M - \theta$ relations of the model with local buckling mechanism shown in Fig. 6(d) are analyzed under the several values of n by the method of analysis mensioned in section 4. The axial compressive load ratio n as a standard value must be decided. It may be selected in considering the values in the actual columns of building frames. In this study, $n = 0.1$ is chosen as a standard value. The behavior of a column with $B/t = 50$ and $n = 0.1$ is defined as a standard one which is demanded for steel framed structures having minimum strength and deformation capacity (Fig. 8).

Second, $M - \theta$ relations of the models shown in Fig. 6(c) with several values of $B/t > 50$ are analyzed under $n = 0$. The numerical results are shown in Fig. 9. Then, the standard behavior of a hollow tube is compared with that of a concrete filled tube in the view point of equal energy absorption capacity at the same displacement θ / θ_{pc}. Changing the value of θ / θ_{pc} = 5, 7.5, 10, the energy

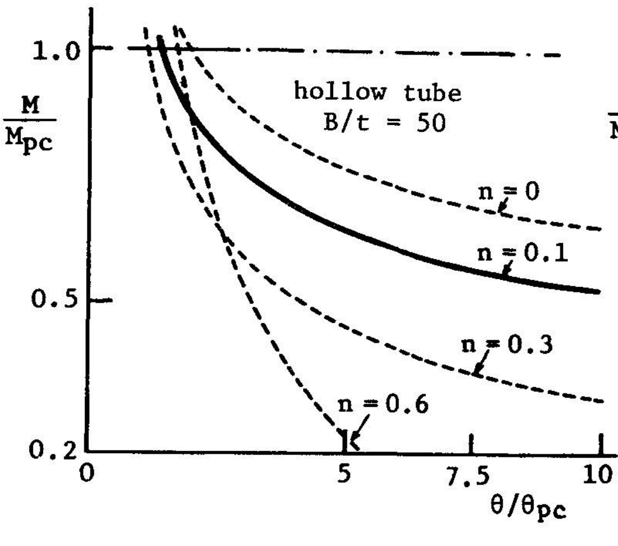

Fig. 8 Behavior of Hollow Tubes

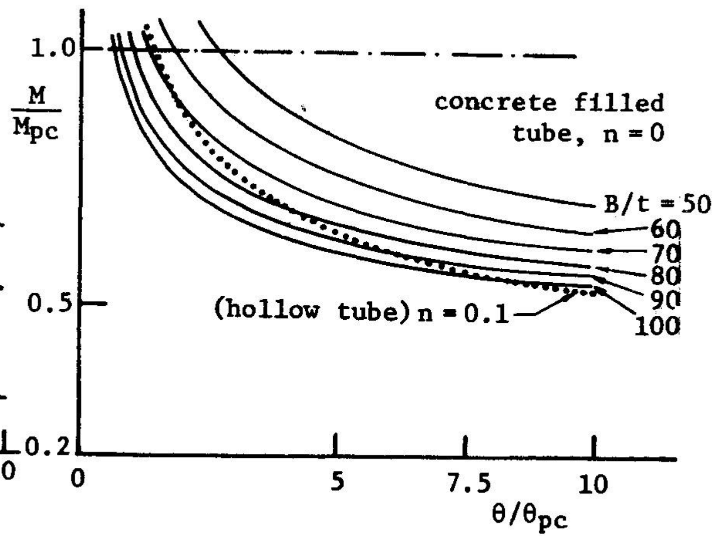

Fig. 9 Behavior of Concrete Filled Tubes

absorption capacity of two columns is compared in Fig. 10. In the figure, the value of 1.0 in the ordinate means that the two columns have equal energy absorption capacity. From this figure, a new limiting value 75 is found conservatively for mild steel tubes with $\sigma_y = 23.5$ KN/cm^2. It is 1.5 times of that for hollow tubular columns. The new values for other grades of steel are obtained by the same method. The numerical results show that the same rate for mild steel may be used for high strength steel.

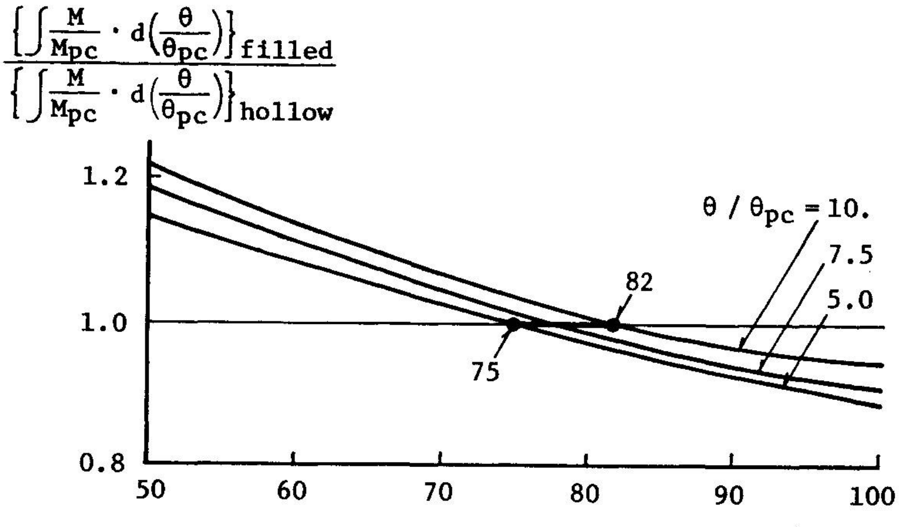

Fig. 10 Limiting Width-to-Thickness Ratio

Figure 11 shows the behavior of the frames composed of the concrete filled steel tubular columns with B/t = 68 (d/t = 64) [5]. The actual yield point of the tubes is 28.8 KN/cm^2, the limiting value of d/t becomes about 43. Then the value of d/t = 64 is 1.5 times of the limiting value. From the figure, it is observed that the frame can be expected to behave in ductile manner and attain the mechanism line ignored local buckling. This fact supports that a proposed limit value is reasonable to be used in the design of concrete filled columns.

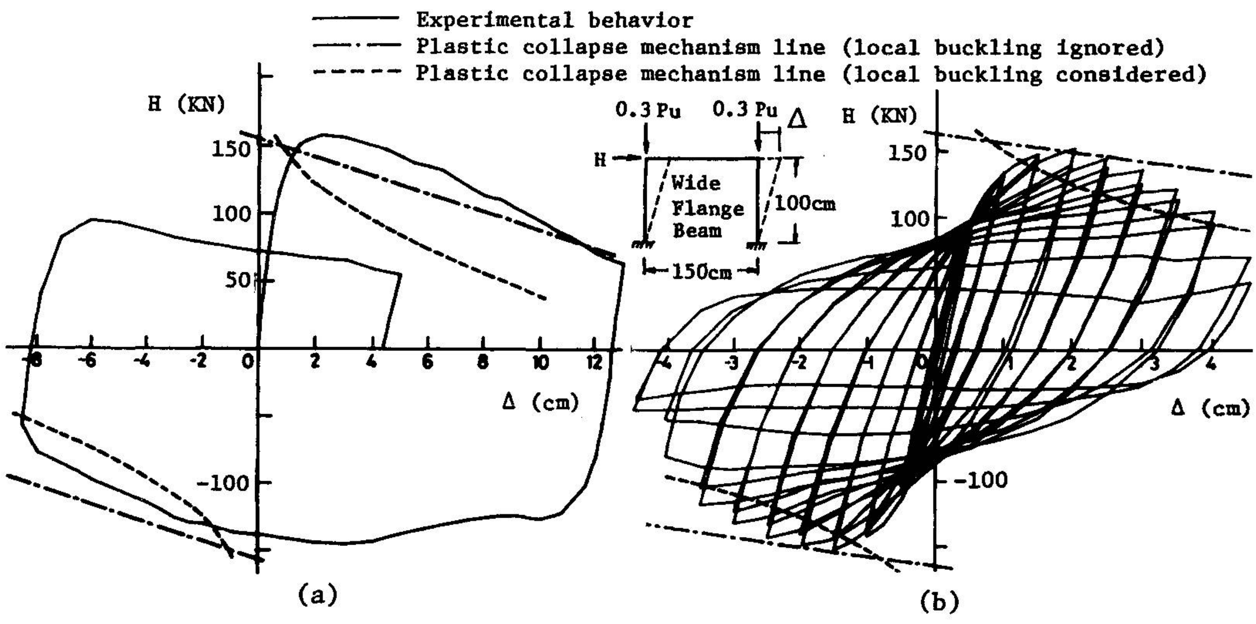

Fig. 11 Behavior of Frames Composed of Columns with B/t = 68.

6. CONCLUSION

A new limiting value of the width-to-thickness ratio of plate elements of concrete filled steel square tubular columns is proposed on the basis of the numerical results obtained by plastic limit analysis. It is about 1.5 times of that for hollow tubular columns.

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