Transactions of the **13th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 13), Escola de Engenharia - Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil, August 13-18, 1995

Optimization of concrete-filled steel tube structures for geometry and mechanics

Kouznetsova, E.E.
Russian - America J. Venture "SATECH" Ltd., Moscow, Russia

ABSTRACT: A concrete filled steel tube presents a composite element allowing to sufficiently enhance safety and carrying capacity of a civil-engineering structure and reduce its mass. Such elements are known to be planned for application in containment structures of NPP new development.

This paper proposes a generalized mechanical model of concrete-filled steel tube element and, on its basis, a method to determine an ultimate stress-strain state and carrying capacity analysis. The normal operation of the model has been proved by a comparison of numerical results obtained with its use and published experimental data.

The functions of carrying capacity from geometrical and mechanical characteristics of concrete filled steel tube structure have been studied and its optimization method according to these characteristics has been defined. It is shown that there is a single value of concrete filled steel tube parameter relationship defining an optimum point, that is, a maximum increase of concrete filled steel tube structure carrying capacity in comparison to a traditional reinforced concrete one.

1 INTRODUCTION

The studies review of concrete filled steel tube structures (CFST structures) has shown that there are conflicting statements on how a tube is acting in an ultimate state. Some authors are asserting that it acts mainly only in a longitudinal direction as a longitudinal reinforcement, the others — in an orthogonal direction using for a tube the term "goke" the third suppose that a tube of the composite structure can reach both "longitudinal" and "orthogonal" yields depending on its thickness. Herein, it is considered that so-called "thin wall" tubes the reinforcement percentage of which is $\mu_s < 7 \sim 9$ % achieve in an ultimate state an "orthogonal" yield, "thick wall" ($\mu_s = A_s/A_b \cdot 100\% > 7 - 9$ %) — "longitudinal". Out of this the authors supporting the third standpoint arrive at a conclusion that the thinner the tube the higher is the efficiency of its use.

Also there is no common opinion in the question of a concrete strength used in a composite element.

The most optimal ratio of geometrical and mechanical characteristics of a composite structure by the mechanical and geometrical parameter suggested by Prof. Luksha $\mu_s R_y/R_b$ lies in the range 1 to 3 (1). But in his studies Dr. Kvyadaras (2) has established that the maximum carrying capacity of a concrete filled steel tube is achieved at parameter values equal 0,1-1,0.

The opinions of investigators are also conflicting under consideration of how loads are applied to an element (to the whole cross-section or only to a concrete core), that is in this work an attempt has been made to solve the uncovered contradictions by developing a universal analysis method for concrete filled steel tube structures.

2 AXIALLY COMPRESSED SHORT MEMBER STRENGTH

The problem solution in determining a stressed-strain state of a concrete filled steel tube structure exposed to an axial load in an ultimate state is based on the following suppositions:

1) a concrete-filled steel tube structure is loaded with a short-term load;

2) the core material is isotropic and with respect to it the experimental parameters of strength and deformation by G.G.Golomentsev are adopted;

$$\sigma^b{}_z = R_b + (1 + 2.9\,(R_b/\sigma_\rho)^{1/3})\cdot\sigma_\rho\,,\quad \varepsilon_z = \varepsilon_0 + \sigma_\rho/8.6\,R_b \ln R_b\,;$$

3) the tube material is transversially isotropic and follow the Prandtle diagram. Tube is subjected to the criteria of the Tresca-Sen-Venan plasticity $\sigma^s{}_z = R_y - \sigma^s{}_\theta$;

4) in composite structure loading the equality of radial replacements of the tube and the core is observed;

$$\frac{r}{\widetilde{E}_s}\left[\nu_s R_y + \sigma_\rho\left(\frac{R_0}{\delta}(1-\nu_s)+\nu_s\right)\right] = \frac{r}{\widetilde{E}_b}\left[\nu_b R_b + \sigma_\rho\left(\nu_b\,(1-\widetilde{k})-1\right)\right];$$

5) the axial compression load is transmitted onto a concrete core and a tube, and it is suggested to have the equality of axial core and tube deformations $\varepsilon_z^s = \varepsilon_z^b$;

6) in the case when the axial pressure is transmitted only onto the concrete core it is suggested to have no friction between the core and the tube;

7) in the ultimate state due to the longitudinal expansion the core undergoes a three-axial stressed state (a cylindrical compression) (Fig. 1);

8) in the ultimate state the steel is in the state of bi-axial uneven compression with tension (Fig. 1).

On the basis of the given suppositions there was obtained a formula of a lateral pressure of concrete core onto steel tube in the ultimate state:

$$\sigma_\rho = -\frac{\nu_s R_y - \widetilde{n}\,\nu_b R_b}{\frac{R_0}{\delta}(1-\nu_s) + \widetilde{n}\,(\widetilde{k}\,\nu_b + 1 - \nu_b) + \nu_s}\,, \qquad (1)$$

where $\widetilde{n} = \widetilde{E}_s/\widetilde{E}_b$; $\widetilde{E}_s$, $\widetilde{E}_b$ — secant (plastic) modules of steel and concrete in the ultimate state determined in the result of the iteration process; $\widetilde{k}$ — variable coefficient of lateral pressure efficiency determined by the Solomentsev and Smirnov formula $\widetilde{k} = 1 + 2.9\,(R_b/\sigma_\rho)^{1/3}$; ν_s , ν_b — Poisson's ration of steel and concrete; R_y — yield limit of steel; R_b — ultimate strength of concrete.

To determine axial ultimate deformations an empirical formula obtained by the author on the basis of the Solomentsev experimental data is used:

$$\varepsilon_z = \varepsilon_0 + \sigma_\rho/8.6\,R_b \ln R_b$$

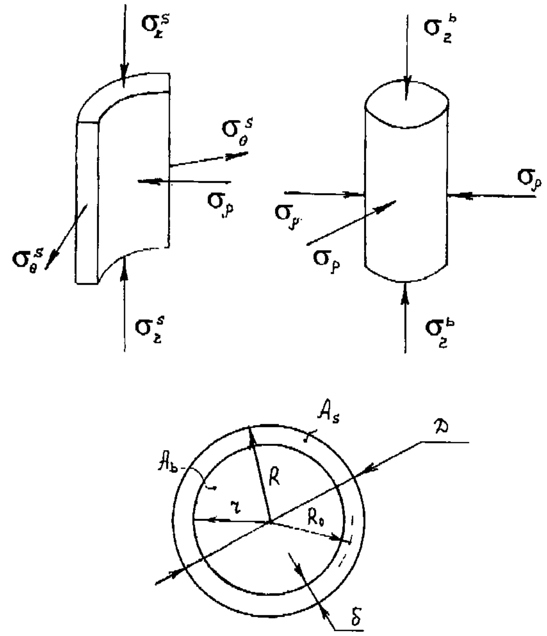

Fig.1. Concrete filled steel tube element stress state and its geometrical characteristics

where $\varepsilon_0 = 0.002$.

From zero equality of external and internal forces projection onto the member's longitudinal axis a concrete-filled steel tube carrying capacity in the ultimate state is determined:

$$N = \sigma_z^s A_s + (R_b + \bar{k}\,\sigma_p) A_b \ .$$

To solve this problem a computer program was set up.

The formula analysis shows that it corresponds to all special cases:

- the tube and core are made of the same material, then the plastic modules and the strength of a tube and core material are equal: $\tilde{n} = \tilde{E}_s/\tilde{E}_b = 1$; $R_y = R_b$. Taking into account that in the ultimate state $\nu_s = \nu_b$, obtained a zero value of the core pressure on the tube $\sigma_p = 0$;

- the tube material is not as strong as the core material: $\nu_s R_y < \tilde{n}\,\nu_b R_b$. This means that the lateral pressure will exceed zero, that is, extending;

- in applying the load only to the concrete core the axial pressure $\sigma_z^s = 0$ then $\tilde{n} = 0$. Under $\nu_s = \nu_b = 0.5$, obtain $\sigma_p = R_y\,\delta/R_0$ and this is the same as the known formula to determine a stress in the tube from the internal pressure. Besides, this value is a maximum possible one under the given suppositions and from here it follows that the given type of loading is more rational than the load applications to the whole cross-section of the CFST structure;

- in the case of the absence of one of the composite structure components the lateral pressure of interaction is equal to zero. For example the concrete-filled steel tube has no concrete core then:

$$\sigma_p = -\frac{\tilde{E}_b\,\nu_s R_y - \tilde{E}_s\,\nu_b R_b}{R_0\,(\,1 - \nu_s\,)/\delta + \tilde{n}\,(\,\bar{k}\,\nu_b + 1 - \nu_b\,) + \nu_s} = 0\ .$$

Table gives a comparison of analysis results by formula (1) and experimental data from Kvyadaras's paper (3).

Table 1

# samples	$D \cdot \delta$ mm	R_b MPa	R_y MPa	Nexp kN	Analysis by formula							
					Dr. Kvyadaras		Dr. Kikin		Prof. Luksha		Author's formula	
					Ncal kN	Nexp/Ncal	Ncal kN	Nexp/Ncal	Ncal kN	Nexp/Ncal	Ncal kN	Nexp/Ncal
11-1	300x3	25.9	280	3610	3575	1.010	3703	0.975	3239	1.114	3991.5	0.904
11-2	"	"	"	3600	"	1.007	"	0.974	"	1.111	"	0.902
12-7	121x4	26.9	345	954	963	0.990	945	1.009	1060	0.990	1071.4	0.890
12-10	"	"	340	930	955	0.973	938	0.991	1050	0.886	1071.4	0.968
13-2	300x2	28.6	280	3600	3600	1.000	3610	0.997	3000	1.200	3705.2	0.972
13-5	"	"	"	"	"	"	"	"	"	"	"	"
14-4	300x5	29.7	280	5000	4417	1.132	4310	1.160	4314	1.159	5245.4	0.953
14-5	"	"	"	4600	"	1.042	"	1.067	"	1.066	"	0.877
14-6	300x3	"	"	4410	3949	1.117	3880	1.137	3504	1.259	4333.5	1.018
14-7	"	"	"	4200	"	1.064	"	1.083	"	1.200	"	0.969
16-1	300x4	32.8	"	5100	4481	1.138	4233	1.205	4142	1.231	5097.8	1.000
16-2	300x3	"	"	4680	4250	1.101	4019	1.165	3738	1.252	4609.8	1.015
16-3	300x2	"	"	3840	4017	0.956	3803	1.010	3788	1.014	4058.4	0.946

	Dr. Kvyadaras	Dr. Kikin	Prof. Luksha	Author's formula
Mean value	1.041	1.059	1.123	0.953
Standard	0.061	0.079	0.120	0.045
Variation coefficient	5.83 %	7.45 %	10.69 %	4.71 %

3 NUMERIC STUDIES OF A CONCRETE-FILLED STEEL TUBE BEHAVIOR DEPENDING ON ITS MECHANICAL AND GEOMETRICAL CHARACTERISTICS

Charts $\sigma_\rho/\sigma_\rho^{max} - R_0/\delta$ (Fig. 2) constructed on the basis of the proposed analysis method allow to determine the boundary between "thick wall" tubes for which in the ultimate state $\sigma_z \neq 0$, $\sigma_\rho < \sigma^{max}\rho$ and "thin wall" ones which have $\sigma_z = 0$ and $\sigma_\rho = \sigma^{max}\rho$. A different scope of the charts depending on the relationship of steel and concrete strength R_y/R_b shows that the existing classification of tubes to the thin and the thick by a fixed value of an element reinforcement per cent ($\mu_s = A_s \cdot 100\,\% / A_b = 7 - 9\,\%$) is incorrect. The more difference in their strength the thinner a tube can be with reaching a maximum efficiency of material use.

The point A_i is a critical one not only from the standpoint of the form of an ultimate state but also from the position of a carrying capacity. The charts in Fig. 3 constructed for the same CFST structures that were shown in the previous Figure indicate that the maximum relative carrying capacity of elements N/N_0 is achieved namely under values (R_0/δ)$_{crit,i}$ corresponding to these points ($N_0 = R_y A_s + R_b A_b$). Herein, the "concrete

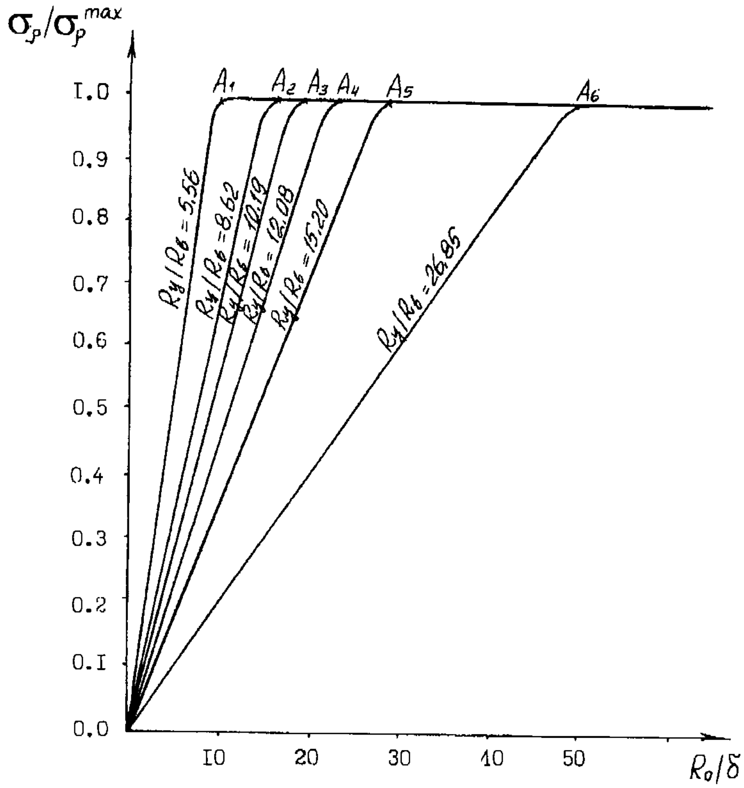

Fig. 2

filled steel tube" effect (the increment of a carrying capacity due to the tube pressure to the concrete) achieves 60 per cent.

As seen from Fig. 3, the maximum values N/N_0 are achieved at the same value of a mechanical and geometrical parameter for all charts. It permits to arrive at a conclusion that there is one single value of a mechanical and geometrical parameter characterizing the optimal combination of strength properties and CFST element geometry. The parameter value is equal to $\mu_s R_y / R_b = 2\, tg\alpha = 0{,}7536$, where α - the slope angle of a linear chart $R_y / R_b - (R_0 / \delta)_{crit}$.

To solve the problem what concrete - low or high strength - is more effective for use in a composite element a numeric experiment was carried out. As a result, there were obtained graphic depends $\sigma_p - R_b$ (Fig. 4). Proceeding from the fact that the obtained angle of the slope for all charts $\sigma_p - R_b$ is the same and equals α, it can be stated that the most rational value $R_{b\,i}$ for any combination $(\mu_s R_y)_i$ is that which corresponds to a break point of given chart.

As seen, the range of optimal values α is very wide and it can not be unambiguously that low strength concretes are more effective than the high strength an visa versa. The calculations shown that for a fixed combination $\mu_s R_y$ there is a single optimal value $R_b = \mu_s R_y / 2\, tg\, \alpha = \mu_s R_y / 0.7536$.

It was found out that using the value a one can solve a problem of determining a stressed-strain state of a concrete-filled steel tube in the ultimate state avoiding complex

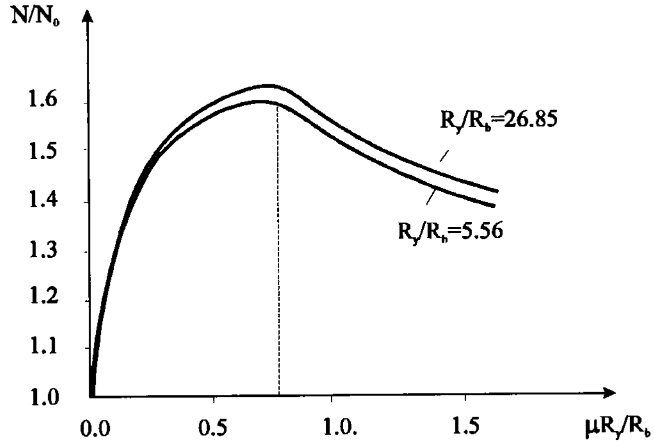

Fig. 3

calculations. Besides, all element parameters would be selected in a optimal manner and produce a maximum increment of carrying capacity equal to 60 per cent.

In order to prove this statement it is necessary to specify a scometry of the element cross-section (μ_s) and steel strength (R_y). Herein, the prison concrete strength will be equal to $R_b = \mu_s R_y / 2\ tg\alpha$. As follows from the charts (Fig. 2), the points of a maximum increment of carrying capacity correspond the value of a lateral pressure

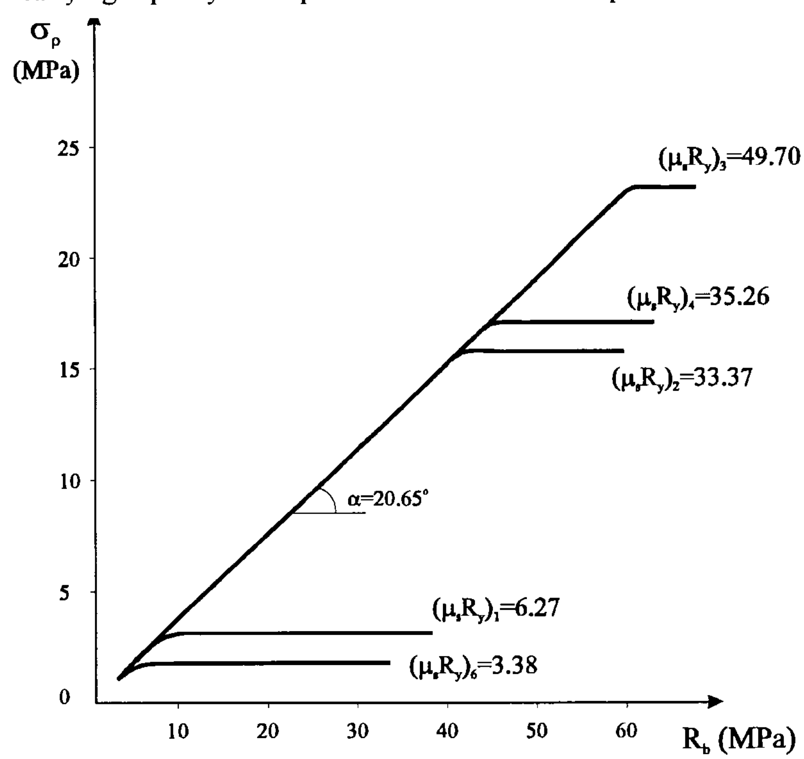

Fig. 4

$\sigma_\rho = \sigma^{max}{}_\rho = R_y\, \delta / R_0$. Thus, by obtaining the value of a lateral pressure one can determine the carrying capacity of an CFST element by formula:

$$N = (R_b + \bar{k}\sigma^{max}\rho) A_b .$$

4 CONCLUSION

The carrying capacity of concrete filled steel tube structures must be determined in considering two conditions of strain compatibility (axial and radial), in accounting plastic properties of materials and the way of load application. Herein, ultimate axial strains can reach values exceeding by order the elastic ones.

The conducted investigations have allowed to describe by one formula a stressed behavior of the "thin wall" and "thick wall" concrete-filled steel tube elements. The calculations have established that these notions are conventional and determined by a complex of geometrical and strength parameters of a CFST structure.

It has been shown that there is the only value of an optimal mechanical and geometrical parameter $\mu_s R_y / R_b = 0.7536$ at which the increment of CFST structure carrying capacity, comparing with reinforced concrete structure carrying capacity is achieving the maximum 60 per cent.

The study of CFST structure behavior by the developed method has shown that the selection of a concrete strength in an optimal solution is ambiguous and depends on a geometry and strength of tube steel. For a tube with the preset strength there can be effective both a normal concrete and a high strength concrete depending on R_0/δ .

REFERENCES

Лукша Л.К. Прочность трубобетона. —Мн.: Вышейшая школа.—1977.
Квядарас А.Б. Прочность бетона, заключенного в стальную трубу //Научные труды ВУЗов Литовской ССР. Оценка прочностибетона и железобетона (Железобетонные конструкции №14), В., 1984, с.71-82.
Квядарас А.Б. К предельным состояниям комплексных конструкций//В сб.: Предельое состояние металлических строительных конструкций. — Карловы Вары. —7.—9.4.1981. —Дом техники Плзень. —1981. —с.46-54.