



# Innovative Experimentation on Hollow Cylindrical Shells of Reinforced Concrete under Axial Compressive Load

Pronoy Roy Chowdhury, Partha Ghosh

**Abstract:** Reinforced concrete elevated water tanks supported on shaft type staging system are popularly constructed now a days for storage of water for water supply schemes. If slip form is used for casting of the shaft staging, the water towers generally require lesser time for construction. Elevated water tanks are top heavy structure especially in the tank full condition. It is often a critical question in structural design that what should be the proper structural model adopted for design of such class of structure. Should the shaft be designed as a hollow cylindrical column subjected to axial compression or is it essentially a R.C. cylindrical shell subjected to membrane forces under axial compression. To better understand it is proposed to cast such R.C. shells and after water curing for 28 days shall be subjected to axial compressive load in a compressive strength testing machine. The failure pattern of the shells shall be observed critically to get a proper understanding of behavior of such R.C shaft supported elevated water tank structures.

**Keywords:** Shaft staging system, R.C. shell, axial compression, elevated water tanks.

## I. INTRODUCTION:

The supporting staging system of Reinforced Concrete elevated water tanks are generally of two types i) Frame type staging of beam & column ii) shaft type staging made of R.C. hollow cylindrical shells.

Now-a-days at many Water Supply Schemes, the overhead reservoir (elevated water tank) is constructed with Reinforced Concrete shaft type staging because it is aesthetically beautiful, and construction can be done in relatively lesser time in comparison with frame type staging. But there are many incidents of structural failure of R.C. elevated water tanks especially during severe seismic events [1,2]. It is found that in general shaft supported water tanks are more vulnerable to failure than frame supported water tanks especially during earthquakes. Some reports on failure of elevated water tanks, supported on shaft staging has been done by researchers during construction and also during filling of water in the newly constructed tank before commissioning [3].

Failure of shaft supported elevated water tanks due to by various reasons are enumerated below:

- i) Failure takes place due to effects of lateral forces such as severe cyclonic wind & seismic forces.
- ii) Failure during filling water in tanks.
- iii) Failure may also take place due to foundation settlement.

Thus, it is clearly understood that the structural behavior of shaft supports involves loads, stresses and constructional aspect of different perspectives. Structural stability of shafts should be checked against wind & earthquake forces guided by BIS codes IS 1893-2014 (Part-2) [4] and IS-875 (Part-3) [5]. Detailed study on structural behavior against wind & earthquake forces have been done by researches elsewhere [6].

However, in this paper mainly behavior of R.C. hollow cylindrical shafts against axial compressive load is observed critically, by casting R.C. cylindrical shells with wire mesh reinforcement and after necessary curing subjecting these cylinder shells to axial compressive force in compression testing machine upto failure and then taking note of the failure patterns.

## II. STRUCTURAL ASPECTS:

Researchers have the opinion that R.C. shaft supported water tanks are prone to 'Sudden Collapse' [7] under axial loads. It is quite difficult to arrive at the proper criteria for structural stability and behavior of the shaft staging. Under axial loads the shaft is a solitary hollow cylindrical reinforced concrete column. While under the effect of lateral load of wind or earthquake the shaft carries axial load & also bends as a cantilever about the base at foundation level. Thus, the hollow shaft is subjected to axial load & uniaxial bending. If the height of shaft is long and slender it may have tendency of global buckling as observed in long columns. Whereas at the locations of ventilation opening & at places where there is inadequate compaction, honeycomb etc. tendency of local buckling may take place at those locations.

Instability of hollow cylindrical reinforced concrete shaft staging may take place due to various reasons which are enumerated below:

- i) Constructional defect may cause non-verticality of shaft.
- ii) Honey combing of concrete may take place due to inadequate compaction.
- iii) Bulging out of concrete may take place at the junction of subsequent lift of slip form.
- iv) Non-Concentric load application may take place from constructional defects

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- v) Stress concentration may take place in the shaft to accommodate doors & windows for ventilation purpose.
- vi) Inadequate compaction of foundation soil may lead to large foundation settlement due to water load when the tank is filled up

From earthquake reconnaissance data it is observed that at many locations shaft supports of elevated under tanks has badly crumbled [8]. The primary behavior of elevated water tanks under lateral forces is flexural in nature. During earthquake the water tank on shaft is subjected to lateral sway inducing circumferential flexural stress in the shaft. The present BIS code of practice for shaft supported elevated tank has adopted the provisions of design of reinforced concrete chimney [9] against flexural forces. But structurally chimney & elevated water tanks are essentially two different classes of structure. While tall Chimney is a slender structure of longer natural period, shaft supported elevated water tank is a short to medium period system. Elevated water tanks are top heavy inverted pendulum structures. Among the shaft supported & frame supported elevated water tanks, shaft supported system are relatively stiffer than the frame supported systems.

The shaft being a hollow column, as per BIS codes of practice IS-456-2000 [10], clause no. 26.5.3.1 (a) minimum reinforcement to be provided in column is 0.8% of the gross concrete area. Whereas as per clause no. 8.2.2.1 of IS-11682 [11], the minimum area of vertical reinforcement in the shaft is only 0.25% of the concrete area of the shaft cross-section. The reinforcement is preferably provided in two layers. May be this reduction in area of steel in mainly on the ground that 0.8% steel would cause reinforcement congestion in the thin shell of the shaft making compaction of concrete very difficult and also major stresses in the shaft in membrane stress and bending stress is very less. Shaft is an axisymmetric reinforced concrete shell. Thus, under the effect of a heavy axial load as in the case of largest water tanks, shafts may have a tendency to buckle. Buckling of shaft as a whole may be classified into global & local buckling. It is known that Global buckling failure is generally observed in the case of long columns. As per clause no. B-3.3 of IS-456 if the ratio  $l_{eff}/r_{min} < 40$  it is considered a short column which fails by crushing of material under axial compression. Roark in his celebrated book "Formulas for stress and strain" [12] comments, under the section for local buckling that, "If a column is composed wholly or in part of thin material local buckling may occur at an unit load less than that required to cause failure of the column as a whole", literature on symmetrical buckling of Hollow cylindrical thin shell under action of uniform axial compression is available. The theoretical expression for critical stress for buckling is given by,

$$\sigma_{cr} = \frac{Eh}{a\sqrt{3(1-\vartheta^2)}} \quad (i) \text{ where,}$$

$\sigma_{cr}$  = Theoretical critical stress for buckling,  
 $E$  = modulus of elasticity,  
 $a$  = radius of the shell,  
 $h$  = thickness of the shell wall,  
 $\vartheta$  = Poisson ratio.

The expression (i) was derived mathematically from the differential equation for symmetrical deflection of cylindrical shells given by the form

$$D \frac{d^4 w}{dx^4} + N_x \frac{d^2 w}{dx^2} + Eh \frac{w}{a^2} = 0 \quad (ii)$$

Where,  $D$  = flexural rigidity of shell =  $\frac{Eh^3}{12(1-\vartheta^2)}$ ,  
 $N_x$  = axial compressive force acting on the shell,  
 $w$  = displacement,  
 $a$  = radius of cylindrical shell,  
 $h$  = thickness of the shell wall,  
 $\vartheta$  = Poisson ratio.

Expression (i) indicates that the critical stress for buckling of cylindrical shell is independent of the length of the shell. Many experiments were conducted to gain knowledge on the buckling behavior of cylindrical shells under compressive loads such experiments were mostly conducted with metallic shells [13] to be used for construction of air crafts. The practical validity of the expression (i) was also investigated extensive photographs of buckling of thin metallic shells. (Made of brass or duralumin) are available in the book 'Theory of elastic stability' [14] by Timoshenko. Strength of thin metallic shells used as columns were evaluated by researchers elsewhere [15]. The strength of thin cylindrical shells as column has become a matter of interest among structural engineers as elevated steel tanks of conical bottom was required to be constructed for which the stand pipe functioned as column to carry the weight of tank and retained liquid. It was generally observed that in all the experiments the theoretical buckling stress was not reached. The highest value of stress that was achieved was only about 60% of the theoretical value. The failure was almost sudden accompanied by large vertical deformation and sudden drop of load in the load testing machine. While a lot of experimental data is available on axial compression of metallic thin shells under compressive load not much data is available on reinforced concrete cylindrical shells under axial compression.

The BIS Code IS-11682 vide clause no. 8.2.1 gives the minimum thickness of concrete shell for shaft staging as 150mm up to 6m center to center diameter of the shaft staging. This is the minimum thickness permitting the formwork to be moved without causing any tearing in the shaft concrete [16]. Beyond 6 m the center to center diameter the minimum shaft thickness is given by,

$$150 + \frac{(D-6000)}{120} \quad (iii)$$

Where,  $D$  = diameter of the shaft in mm.

For elevated water tanks center to center diameter of the supporting shaft staging may vary from 3.5 m for smallest capacity tank such as 150 m<sup>3</sup> to even 10.0 m for bigger tank capacities. The above codal provision vide clause no. 8.2.5 specifies that the outer cover to reinforcement of shaft shall be at least 40mm and inner cover is 25mm. The minimum diameter of vertical reinforcement provided is 12mm tor bar provided in two layers and 10mm tor bar horizontal rings to be provided. Now net thickness of concrete available if 150mm thick shell is provided = (150 - 40 - 25 - 2 x 12 - 2 x 10) mm = 41 mm  $\approx$  40 mm.

Again, achieving uniform compaction within the annular space of the form work of slip form is very difficult. Even with the application of needle vibrator uniform compaction of concrete is not achieved.

So, the shaft has many locations of honeycomb. Due to bulging of formwork at the joints formed due to successive lift of slip form, formation of honeycomb is the most. Hence with 150mm thickness of shaft wall the actual effective thickness of concrete is much less and concrete portion generally bears the compressive load of the tank & the retained water. This may often be the cause of sudden failure of the shaft during filling of the tank. With the advent of sophisticated finite element software's many studies have been conducted on wrinkling or buckling of thin shells. Such results are quite accurate for metallic shells. Metallic shells are homogenous in nature and are manufactured in factory condition with good quality control. Whereas reinforced concrete is a non-homogenous material, generally cast at site condition with lot of imperfection, honeycomb etc. Material heterogeneity, casting & workmanship defect, honeycomb etc. cannot be effectively modeled in finite element software [17, 18]. Thus, it becomes essential to undertake actual experiment to supplement the available knowledge.

In this paper structural behaviour of cylindrical shells of reinforced concrete are critically evaluated being subjected to compressive force at compressive strength testing machine in pursuit to understand the actual performance of such structures which shall be helpful in proper design of shaft staging of elevated water tanks.

### III. EXPERIMENTAL METHODOLOGY:

The experimental method involves casting hollow cylindrical shells of reinforced concrete. Cylindrical shells were cast in specially designed hollow cylindrical mould which were fabricated for the purpose of the experiment. Five nos. such mould of different diameter and 300mm height were fabricated (detailed dimensions are given in fig no.1 & table no.1) steel wire mesh is used as reinforcing material. The concrete used for casting the reinforced concrete cylinders are of three grades M25, M30 & M35 respectively. The cement used for casting the hollow cylindrical shells was 43 grade Ordinary Portland Cement. Five numbers hollow cylindrical shells have been cast for each grade of concrete. The annular opening between the outer and inner diameter of the mould is of 10 mm average thickness.

Physically it was not possible to cast shell of lesser thickness because it is required to accommodate the wire mesh and stone grit which was used for casting the shells. As the annular space was very small, to ensure smooth flow of concrete in the annular space and to avoid honeycombing & voids, the slump of green concrete was kept as high as 100mm with the use of admixture (super plasticizer) having a trade name of Master Glenium 123[19], a water reducing admixture of chemical composition Poly Carboxylic Ether (PCE). Stone grit with 85% passing through the 4.75 mm IS-sieve and 100% retained on 2.36mm IS sieve has been used as a substitute for crushed stone aggregate. As relatively high slump concrete is used it easily flowed passed the wire mesh uniformly filling all corners of the cylindrical mould. Striking the shell was done externally for expulsion of air bubble and to obtain a homogeneous concrete. Simultaneously 1 set of 3 cubes of 15 cm<sup>3</sup> was cast with above referred concrete mix for each of the grades such as M25, M30 & M35 both the cylindrical shells and cubes were immersed in water for curing for 28 days. And then

they were tested for compressive strength in compressive strength testing machine of 1000 KN capacity. The reinforced concrete shells were measured carefully with accurate scale & vernier calipers before and after compressive strength test. The experimental facility of the Department of Construction Engineering, Jadavpur University, Second Campus at Salt Lake was used for conducting the experimental study. (Detailed Photographic documentation is given in fig nos. 2, 3, 4 & 5)

**RESULT & DISCUSSION:** A set of 5 numbers hollow cylindrical reinforced concrete shell of three different concrete grade including M25, M30 & M35 respectively has been subjected to compressive strength test and also the concrete cubes were tested the results are tabulated in the table no. 2 & 3 respectively.

The tabulated data yields the following observations:

- i) The cube test reveals that the strength of concrete used for concrete used for casting the shells are of adequate strength.
- ii) The dimensions of the hollow reinforced concrete shells were kept in the same proportion as they occur in case of actual shaft staging of elevated water tanks. It is found that the ratio of  $l_{eff} / r_{min} < 40$  in case of all the five samples being tested for compression strength.
- iii) In general, the failure patterns of hollow reinforced concrete cylinders were brittle in nature, crushing of concrete had taken place at the top & the bottom edges.
- iv) The collapse of the concrete shells took place suddenly. Although strength of the concrete cubes were adequate (refer table no.2) indicating that the concrete mix was satisfactory. But the hollow cylinders got crushed at almost  $1/3^{rd}$  to  $1/4^{th}$  of the compressive strength of the respective concrete grade (refer table no.3).
- v) There is no appreciable change at the central diameter of hollow cylinder after application of compressive load even upto failure.
- vi) No bulging, buckling or wrinkling was observed in the surface of the hollow cylindrical shell after application of axial load even up to failure.
- vii) Inclusion of minimum percentage of reinforced element (wire mesh) did not manifest any ductile behavior to the hollow cylindrical shell.

Thus, from above observations it may be summarized that

- Shaft staging of R.C elevated water tanks has ratio of  $l_{eff} / r_{min}$  lesser than 40 and generally reinforcement in the shaft portion varies from 0.25 to 0.3%. Dimensional ratio of R.C cylindrical shells were kept in the similar range as seen for elevated water tanks and minimum reinforcement has been provided with wire mesh. The shells have failed in material crushing at the top & bottom edges under axial compressive force which is the expected behavior of crushing of short columns.
- Global buckling may be observed in long columns with  $l_{eff} / r_{min} > 40$ , if the staging height of elevated water tanks are increased for requirement of sufficient head in the pipeline distribution system, then tendency of buckling may become prominent.
- Local buckling, wrinkling of metallic cylinder shells under axial compressive force are generally observed if the ratio of radius of shell to shell wall thickness ( $a/h$ ) is generally high.



In metallic shells where (a/h) ratio is 100 and above such buckling becomes very prominent. But for Reinforced Concrete shells with 200mm shell wall thickness, the shaft diameter generally varies from 3500mm for the smallest capacity tanks to about 10000mm for the largest capacity tanks. Thus (a/h) ratio is in the range of 8.75 to 25. In such low (a/h) ratio values buckling is not generally manifested. Metallic shells are generally very thin, metals have much higher values of elastic constants than concrete, hence thicker concrete sections are required for corresponding metallic shells.

- Load carrying capacity of hollow cylindrical reinforced concrete shells are about  $1/3^{\text{rd}}$  to  $1/4^{\text{th}}$  that of cube strength of concrete. Hence, adequate factor of safety is to be applied while calculating load carrying capacity of hollow cylindrical shaft of elevated water tanks.
- Ductility of shaft is much less with provision of minimum reinforcement; hence such structures are expected to have inferior performance against lateral earthquake forces.
- Axial compression failure of shaft at the top & bottom edges has been observed from the experimental work. That is why the junction of tank with shaft & the shaft with the foundation is generally stiffened with provision of top & bottom circular girder.

#### IV. CONCLUSION:

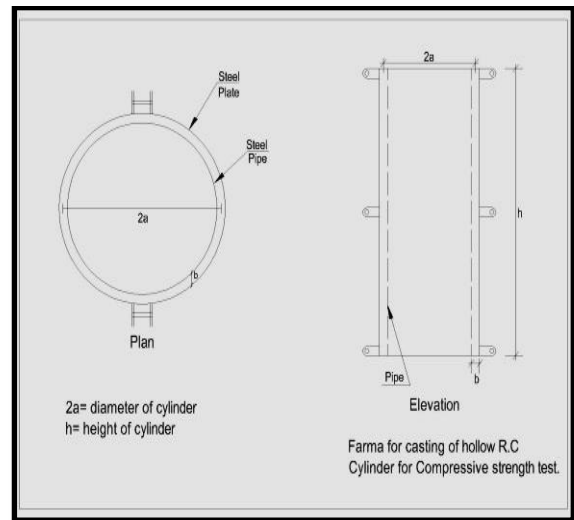
Within the limited scope of the experimental work it may be concluded that in general the structural behavior of reinforced concrete hollow cylindrical shaft of elevated water tank resembles that of a short column under axial compression. Ductility of reinforced concrete shaft with minimum reinforcement is not at all prominent. Thus, such type of staging system for elevated water tanks should be in general avoided in seismic zones IV & V where tendency of severe earthquake is relatively high.

Crippling of shaft staging under axial compression, is not a critical failure mode for reinforced concrete shaft staging for (a/h) ratio which is generally observed in the Overhead Reservoirs. However, a provision for check against buckling should be always kept from the perspective of structural weakness of the shaft due to opening for ventilation, honey combing during casting and also for the large capacity tanks where axial compressive load is very large.

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**Fig no.1 Details of the mould (farma) used for casting of hollow cylinder.**

**Table No.1 dimensions of cylindrical mould (farma)**

Sl no.	h(mm)	2a (mm)	b(mm)
1.	300	90	10
2.	300	120	10
3.	300	150	10
4.	300	180	10
5.	300	225	10



Fig no.2 cylindrical mould and reinforcement cage.



Fig no. 3 assembled mould.



Fig no.3 Mixing of Concrete



Fig no. 4(a), (b) Hollow concrete cylinders being measured



Fig no. 5(a), (b) & (c) showing failure pattern of the hollow reinforced concrete cylinders.

Table No. 2 Characteristic compressive strength of concrete used for casting hollow cylindrical shells

Sl. No.	Grade of Concrete	Crushing strength of concrete cube at 28 days curing			Average Compressive strength (N/mm <sup>2</sup> )
		Cube-I (N/mm <sup>2</sup> )	Cube-II (N/mm <sup>2</sup> )	Cube-III (N/mm <sup>2</sup> )	
1.	M25	27.05	28.45	28.95	28.15
2.	M30	32.21	33.66	33.10	32.99
3.	M35	37.25	38.90	37.45	37.87

Table No. 3 Compressive stress developed at failure in reinforced concrete hollow cylinders

Sl No	Grade of Concrete	Sample Marked	Height of Cylinder	O.D (m)	I.D (mm)	Average thickness (mm)	$l_{eff}/r_{min}$	a/h	Area of C/S of cylinder shell (mm <sup>2</sup> )	Axial load at failure (N)	Compressive stress (N/mm <sup>2</sup> )
1.	M25	C125	300	100	80	10.0	18.7	4.5	2827.4	19085	6.75
		C225	300	130	110	10.0	14.09	6.0	3769.9	32230	8.55
		C325	300	160	140	10.0	11.29	7.5	4712.40	58985	8.27
		C425	300	190	170	10.0	9.41	9.0	5654.80	54500	9.64
		C525	300	235	215	10.0	7.53	11.25	7068.60	79000	11.18
2.	M30	C130	300	100	80	10.0	18.7	4.5	2827.4	25920	9.16
		C230	300	130	110	10.0	14.09	6.0	3769.90	33495	8.88
		C330	300	160	140	10.0	11.29	7.5	4712.40	40040	8.49
		C430	300	190	170	10.0	9.41	9.0	5654.80	55350	9.79
		C530	300	235	215	10.0	7.53	11.25	7068.60	77590	10.98
3.	M35	C135	300	100	80	10.0	18.7	4.5	2827.4	26300	9.30
		C235	300	130	110	10.0	14.09	6.0	3769.90	38780	10.29
		C335	300	180	140	10.0	11.29	7.5	4712.40	46150	9.79
		C435	300	190	170	10.0	9.41	9.0	5654.80	59950	10.60
		C535	300	235	215	10.0	7.53	11.25	7068.60	82500	11.67

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