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Scaling of RC Chimney for the Experimental Investigation under Lateral Load

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Abstract**:** ***Reinforced concrete chimneys are tall industrial structures specially used in power plants to expel waste gases at high enough elevation. Based on the study of various literature available for the subject, various geometrical, material, and loading parameters to be followed to prepare the test specimens are presented in this paper so that the test specimen represents the behaviour of the actual RC chimney. The special construction process required to be followed is described in this paper along with the various analytical checks to be performed before the actual application of lateral loads on test specimens. Different design standards give different design recommendations mainly in terms of the stress-strain curve of concrete and steel. So, various experimental tests performed by applying the lateral load on specially designed and casted test specimens which represents the actual chimney in the field helps the researchers to compare the various design standards and helps the industry to opt for the same.***

Keywords**:** ***RC Chimney, Experimental Study, Geometrical Parameters, Loading Parameters, Material Properties And Checks For The Test Specimens.***

I. INTRODUCTION

Due to the rise in pollution all over the world, environmental control boards of various countries including India imposes very strict rules and regulations to control the pollution. The key factor in the increase of air pollution is the emission of carbon in the atmosphere from various industries and importantly from power plants. As tall chimneys provide means to expel these carbon emissions away from the ground at high elevations, many industries are being forced to construct tall chimneys. As the most suitable material to construct such tall chimneys is concrete reinforced with steel, the construction of RC chimneys is a need of the day. For analysis and design purposes, chimneys are modeled as a cantilever column having a hollow circular section with a small thickness of the shell. For the analysis and design main loads to be considered are:

1. Axial compression due to its self-weight and weight of the lining
2. Bending moment due to lateral loads like wind forces or earthquake forces.

The ultimate strength of the RC chimney section is defined as its capacity to carry ultimate moment, along with its capacity to withstand an axial compressive load resulted in preliminary form self-weight associated with a particular depth of neutral axis within the section.

Limit state design approach for the design of RC chimney sections requires the specification of appropriate stress-strain relationship for concrete and steel for thin-walled hollow circular sections. Different stress-strain relationships have been adopted by various codes for this purpose. In its latest revision i.e. in its 3rd revision, IS: 4998 – 2015 [1] adopted a limit state design approach for the design of RC chimney sections. Before the code has been revised many researchers have done analytical research and experimental research work on this subject. This paper discusses their contribution to the field.

As the RC chimney section (hollow circular section with the thin wall) is quite different from normal beams and column frame structure and hence quite different approach has to be adopted for casting the test specimens that represent the RC chimney for the experimental research work.

Based on the available study of experimental work on RC chimneys, this paper discusses the scaling parameters, casting techniques including concrete mix to be adopted for casting, application technique of the axial and lateral forces and the checks required before application of axial forces that represent the self-weight of the RC chimney.

The draft structure of this paper is organized by dividing the paper into two major sections as follows: Section 2 presents the survey of design codes and research papers that describes the procedures developed for RC chimneys and results of the various experimental tests conducted on RC chimneys. Section 3 finishes the paper that comprises the discussion of research challenges, recommendations, along with future research guidelines.

II. LITERATURE SURVEY

This section presents the survey of RC chimneys, in which section 2.1 surveys the theoretical study on RC chimneys for analysis and design 2.2 reviews the research papers based on an experimental study on RC chimneys.

2.1 Theoretical Study on RC Chimneys for Analysis and Design

S. Sowjanya Lakshmi, Dr. K.Hari Krishna [16] carried out a comparative study between wind loads and earthquake loads on RC chimneys. The main loads considered during the analysis of chimneys were self-weight, wind loads and seismic loads.

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The dynamic component of wind in the analysis was taken as per IS recommendations to moderate the effects due to "vortex shedding". For seismic loading, calculations were made using the response spectrum method. The moment profile was calculated and plotted. The forces due to seismic action were found to be much less than that from the wind actions, and hence earthquake forces would not be a major consideration in the design. Shaikh M. G [17] carried out a similar study and concluded the same.

Saba Rahman et al. [18] compared analytical methods adopted by seven major codes namely CICIND-2011, ACI 307-08, NBCC, IS 4998:2015, AS/NZ 1170.2:2011, Euro code method-I (EN 1991-1-4), and Euro code method-II (EN 1991-1-4). The paper mainly focuses on the across wind analysis and along-wind analysis and presents the basis of the formulations of their codal recommendations. It was concluded that the equivalent static formulas given by the above-mentioned design standards are using either Vickery and Basu model or Ruscheweyh's model. In addition, whilst contrasting disparate codes, how disparate code formulae were attained as of these '2' formulations were illustrated. Using '3' numerical example issues, the contrast of disparate vital code provisions was exhibited and assessed.

Amitha Baiju and Geethu S [19] designed an RC chimney for understanding the lateral deflection's variation at the chimney's top by changing the chimney's height above 275 m. Aimed at the analysis, CED 38:7892 Code of practice for the RC chimney's design was utilized. Bellary in Karnataka was the location chosen aimed at the study. For this study, wind and also temperature were only deemed. For '5' disparate heights, a total of '5' models were chosen. The analysis together with the design was executed. Aimed at the analysis, ANSYS was employed. It was discovered that with the augment in the slender structure's height, the lateral deflection at the chimney's top augmented.

M. Orcun Tokuc and Serdar Soyoz [20] introduced the reliability estimation of a 100.5 m high RC chimney at a glass factory under earthquake forces. A moderate-size earthquake happening closer to the site and a huge earthquake occurring far as of the site was deemed for describing the uncertainties owing to input motion. The uncertainty's influence in structural parameters along with modeling assumptions was deemed. It was deduced that owing to the above-mentioned uncertainties, disparate values were possessed by the chimney's fundamental period. It was perceived that the chimney's failure probability was more in the huge earthquake motions happening far as of the site.

Anusha S et al. [21] introduced the RC chimney's reliability analysis accustomed to WL along with temperature stresses. Utilizing the MC simulation technique, the stress up-crossing's probability was calculated. There was always a chance, however small, that the permissible stress might be exceeded by the induced stress, although deterministically the condition was fulfilled as rendered by the method. It was recommended that it was feasible to keep the failure rate as small as possible by determining the probability distribution for describing the failure rate.

Xuansheng Cheng et al. [22] analyzed the chimney's safety evaluation in the action of wind along with an earthquake on an RC chimney in the Jinchuan Company in China. Utilizing utmost value superposition, the structure's displacement in the RL's action along with the earthquake was examined. Utilizing the equal curvature criterion technique, the stress upon the chimney was estimated in '4' cases. The results exhibited that the displacement limit could fulfill the code necessities aimed at a chimney in WL or regular earthquakes. But, the structural displacement was higher when analogized to other conditions under the merged action of regular earthquakes along with RL.

John L Wilson [23] inspected the behaviour of 4 RC chimneys, which were accustomed to the important ground shaking throughout 2010 with Mw8.8 Chilean earthquake occasion. These RC chimneys were newly built and designed using the latest recommendations for the design of RC chimneys incorporated in the CICIND code, according to which the RC chimneys were designed for ductility. The internal face was straightly associated with the 'Pennguard Block' lining system. The outcomes of the study indicated that every chimney was shown extremely well ductile behaviour, with either no cracking or small circumferential cracks having crack widths not more than 0.2 mm.

Suhee Kim and Hitoshi Shiohara [24] carried out a non-linear dynamic analysis on an RC chimney of height 60 m located at an incineration plant in Kashiwazaki, Japan. The chimney was broken during the Niigata-ken Chuetsu-Oki earthquake in 2007. The effect of the chimney's vertical flexural strength (FS) distribution and the predominant period of the ground motion (GM) were examined. After the study of available reinforcement detailing drawings, the failure was discovered to take place at the section where the FS was locally inadequate. It was affirmed that the chimney was led by high intensity and the long-period GM to react in the higher non-linearity range. An inelastic response's concentration was attracted by the FS discontinuity within the chimney. Franziska Wehr and Reinhard Harte [25] contrasted the chimney's load-bearing capacity estimated through-beam along with shell theory. It was evident that for h/d ratios greater than 30, the design through-beam theory was on the safer side for the preferred example's vertical reinforcement. The load distribution about the circumference was overestimated by the design through-beam theory and produced the wrong outcomes. Conversely, the chimney's load-bearing capacity was overestimated by a linear elastic shell computation. But, utilizing shell theory with non-linear material properties, the stress's realistic distribution in the chimney's cross-section could still be assessed.

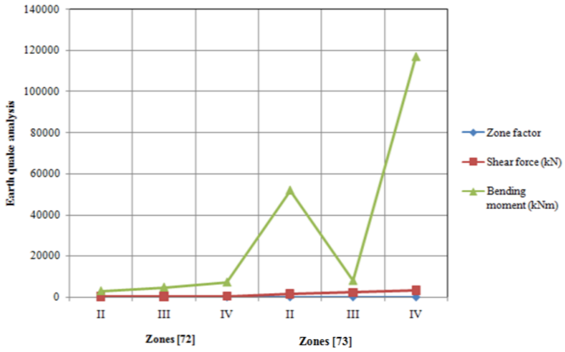
Atef El-Sadat et al. [26] studied the effects of earthquake and wind forces (static and dynamic) on behavior of the regularly utilized chimneys in Egyptian power plants. For the study 3D finite-element software was used. For conducting the parametric study by altering the chimney slenderness ratio (Height/Diameter) either by altering the chimney height or diameter to learn its static and also dynamic behavior, the El-Suez Power Plant chimney was chosen. It was advised to utilize a slenderness ratio not lesser than 13.0. Utilizing less than this ratio, more vertical reinforcement would be attracted either by reducing chimney height or augmenting chimney diameter.

Amit Nagar and Shiva Shankar M [27] carried out the study of RL along with earthquake load impacts on RC chimneys for fundamental wind speed 33 m/sec. In relation to IS: 1893 (part 4): 2005 [14], seismic analysis was performed by time history analysis and wind analysis through along wind effects via gust factor technique according to draft code CED 38 (7892): 2013 (3rd revision of IS 4998 (part 1: 1992) for disparate heights changing as of 150 m to 300 m and also for disparate longitudinal sections, namely uniform, tapered along with uniform-tapered by utilizing the SAP-2000. When contrasted to other types, the RC chimney with more height along with a uniform section would be critical as signified by the results. For both loading cases, the most efficient configuration was found to be consistently tapered.

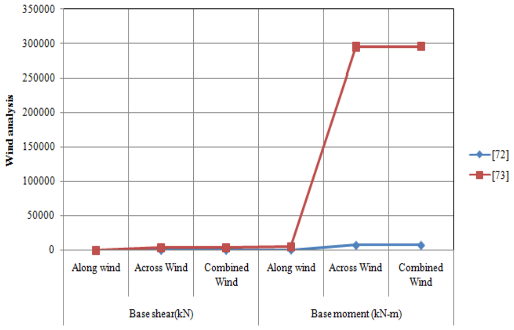
To understand the effects of earthquake and wind analysis, a comparative study has been carried out on RC chimney models utilized by [28] and [29] by the author. Utilizing IS 1893 (part4): 2005 [14], the earthquake analysis and IS: 4998 – 2015 [1], the wind load analysis is executed and results are presented in *Table 1* in form of natural frequencies and corresponding time periods for the 60 m and 100 m RC chimneys. Results of earthquake analysis for zones II, III and IV are presented here in form of shear force and bending moments in “Fig. 1(a)”. It seems that when compared to its preceding zone, there exists at least a 50% enhance in moments in each zone. These are the highest moments attained at the chimney's base. It is to be noted that for this comparative study the chimneys are modeled as cantilever columns with hollow circular sections with lumped mass configuration in STAAD.Pro V8i. The shear force along with bending moment values has increased since the zone factor value augmented as revealed by the results attained as of [28]. Shear force and bending moment values attained as of the wind analysis are represented in “Fig. 1 (b)”. The wind analysis comprises computing along and also across wind effects independently. When analogized to the earthquake forces in Zone II along with Zone III, the wind force’s effects for 55 m/s wind speed was somewhat significant in [29]. As a consequence of the earthquake in Zone III, the moment was approximately equal to the merged moment because of 55 m/s wind speed.

Table- I: Characteristics of RC chimney for free vibration

Reference	Natural Frequency		Time Period	
	1st Mode	*2nd Mode*	*1st Mode*	*2nd Mode*
[28]	0.827	4.147	1.208	0.241
[29]	1.864	9.283	0.492	0.184



(a)



(b)

Fig. 1.Results of earthquake and wind analysis

In comparison with earthquake forces, the wind forces consistently governing the design of the tall RC chimney.

Durgesh C. Rai and others [30] plotted the load-moment interaction curves for hollow circular sections utilizing stress-strain curve specified in IS: 456 – 2000 [2] and compared with interaction curves plotted with working stress conditions and IS: 4998 – 1975 [3] for cracked section analysis and concluded that limit state method should be adopted for hollow circular sections rather than working stress method. K. S. Babu Narayan and Subhash C. Yaragal [31] have developed a computer program to plot the load-moment interaction diagrams and to design the hollow circular section using a simplified rectangular stress block. But neither the stress-strain relationship given in IS: 456 – 2000 [2] nor the rectangular stress block for concrete can be directly used for the thin-walled hollow circular sections like a chimney. P. Srinivasa Rao and Devdas Menon [32] suggested a new stress-strain relationship for concrete and plotted the load-moment interaction curves and compared the same with interaction curves plotted with the provisions of various other well-established codes.

2.2 Experimental Study on RC Chimneys for Analysis and Design

Omote Y and Tekada T in 1975 [33] carried out quasi-static cyclic tests on a model chimney section. The cyclic tests were conducted using a pipe of length 5.0m, outside diameter 800mm and thickness 80mm with 1.3% of longitudinal reinforcement centrally placed. No axial load was applied. The simple beam displayed excellent hysteretic behaviour when subjected to two-point transverse cyclic loading with a constant moment over the central 2.0m region. This test although useful is not directly applicable to RC chimneys which have a D/t ratio of significantly more than 10 and are subjected to the simultaneous bending moment, shear force and axial force. Regan [34] in 1981 tested four hollow cylinders with an external diameter of 800mm, a wall thickness of 40mm and a cantilever length of 2.5m for specimen 1 and 2.0m for others. The load was applied monotonically at the free end via a saddle arrangement. Prestressing wires are used to produce axial stress ratio fc/fck from 0 to 0.08. The longitudinal reinforcement ratio varied from 0.7% to 2.4%, and consist of a mesh on both faces of the thin-walled tube (1.0%).

The mesh used was brittle with failure occurring at the location of the welds at strains of only 0.8%. Shear reinforcement equivalent to 0.5% was placed in specimens 1, 2 and 4 but omitted in specimen 3. The concrete mix used due to the thickness of the model walls was micro-concrete. The test arrangements produced relatively large shear forces with relatively low shear span ratios of 3.3 for specimens 1 and 2.6 for the others. The test arrangements produced relatively large shear forces with relatively low shear span ratios of 3.3 for specimen 1 and 2.6 for the other specimens. The failure mode of specimen 1 was quite brittle with the formation of significant web shear cracks and demonstrates the importance of shear reinforcement. The failure modes associated with specimens 1, 3 and 4 were flexural and initiated by the meshing fracturing in tension prematurely and subsequent spalling of concrete in the compression zone. The study concluded that thin-walled concrete sections were brittle due to the concrete being unconfined both inside and outside and subject to uniform compressive stress. The results of the study undertaken by Regan appeared to be significantly affected by the introduction of very brittle mesh for the longitudinal and shear reinforcement. Fracture of longitudinal steel immediately increased the tensile and compressive strains and hence curvature as the cracks progressed around the circumference and widened. The observations of concrete spalling in the compressive zone appeared to be a secondary effect and probably would not have occurred if the tensile strains had been controlled through yielding and not fracture of the longitudinal reinforcement. The use of brittle longitudinal steel in such tests should be strongly discouraged, as it initiates the development of a brittle failure mode.

Schober H and Schlaich J [35] in 1984 tested five-tube specimens, each of 5m length, the outer diameter of 1200mm and a relatively large 100mm wall thickness. Axial forces were introduced into the tubes via centrally located tendons to achieve axial stress ratios fc/fck that varied from 0 to 0.20. Longitudinal reinforcement ratios varied between 0.45% and 1.64% and consisted of one layer of 10mm deformed bars. The tubes were loaded monotonically with a constant bending moment applied at each and until failure, and hence the effects of shear–flexure interaction were not modeled. The tests confirmed the importance of including the stiffening effect of concrete in tension between the cracks when assessing deformations. The results satisfied the test objectives but were of limited value in understanding the inelastic cyclic behaviour of typical chimney sections. In particular, the low D/t and the absence of shear force and monotonic nature of the loading made extrapolation of the results for an earthquake engineering application impossible.

Zamil A. R. Mokrin and Wadi S. Rumman in 1985 [36] made experimental investigations to determine the ultimate strength and stiffness of RC members with tubular sections subjected to lateral force and axial compression. The experimental results were also compared with the theoretical results obtained from various available design methodologies. Total eight specimens were loaded to failure, out of these four test specimens were loaded monotonically and the rest were loaded cyclically. All the test specimens were 3.25m long, 406mm outside diameter, wall thickness 50mm and with one layer of reinforcement centrally placed. The longitudinal steel ratio varied from 0.5% to 1.0%, and an axial load which was applied using prestressing cables produced an axial stress ratio fc/fck from 0 to 0.08. The simple beam was subjected to two-point loading producing a 1.0m central length of pipe which experienced a constant maximum moment with zero shear, a loading condition that is not typical of cantilever structures such as chimneys. They concluded that the ultimate strength of the test specimens increases with an increase in the percentage of reinforcement, axial compression, or both and does not depend on the loading antiquity. It can also be confirmed from the results of experiments that the ultimate strengths of the test specimen will be higher if test specimens are cyclically loaded with progressively increasing crests, than the ultimate strengths of those test specimens applied with monotonically increasing load. It was also concluded that for practical purposes the designers could conservatively use, the monotonic analysis to calculate ultimate strengths for cyclically loaded test specimens. The moment-curvature diagrams plotted for monotonic tests with three discrete points: (a) at the first crack (b) at yielding of reinforcement and (c) at failure, indicated good hysteretic behaviour under cyclic load but no details of the failure mode or plastic hinge development were discussed. Although the tests used longitudinal steel ratios and axial stress ratios which were realistic, the method of load application and the very low D/t ratio were not typical of chimney structures and hence extrapolation of limited results could not be undertaken with confidence.

Whittaker D [37] in 1988 undertook a very comprehensive study investigating the seismic performance of offshore concrete gravity platform legs. Six specimens of length 3.2m, outside diameter 800mm and a thickness of either 100mm for two test units or 50mm for four test units were constructed as cantilevers and tested using a quasi-static cyclic load applied at the free end. Axial loads were applied via an external actuator with axial stress ratios fc/fck ranging from 0.25 to 0.42. Longitudinal reinforcement ratios varied from 2.3% to 2.9% with the placement of ductile deformed bars of diameter 6mm and 10mm. Shear reinforcement was provided together with through-thickness square ties to provide concrete confinement and prevent buckling of the longitudinal reinforcement. The tests demonstrated that sections subject to significant axial loads and with large longitudinal steel ratios could behave in a ductile manner provided sufficient confinement and anti-buckling steel was provided in form of closed ties to prevent brittle compressive failure modes developing. The tests were thoroughly undertaken and of direct relevance to offshore gravity platforms, but limited use for RC chimneys due to the inclusion of confinement steel and the significantly different; loading regime, section geometry and reinforcement ratios.

Zhan F. A, Park R and Priestley [38] in 1990 tested three pairs of hollow tubes, all of them of length 3.1m and outside diameter 400mm but with the thickness of 94mm, 75mm and 55mm resulting in low D/t ratios of 3.2, 4.3 and 6.3. The tubes were arranged as simple beams and a transverse load was applied to a solid diaphragm located in the center of the beam.

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The objective of the tests was to evaluate the ductility available in the hollow sections which have one layer of confining reinforcement in the form of circular spiral reinforcement located close to the outer face of the shell. All tubes contained a high longitudinal steel reinforcement ratio of 2.6% and a transverse reinforcement ratio of either 1.1% or 1.4%. The axial load applied via jacks having axial stress ratio fc/fck varied from 0.08 to 0.40. The study concluded that the available curvature ductility is significantly influenced by neutral axis depth at the flexural capacity of the column. The ductile behaviour could be expected if the neutral axis was nearer to the unconfined inner face of the tubular section, which also results in a small longitudinal compressive strain. Whereas the brittle behaviour could be observed if the neutral axis was some distance away from the inner face and nearer to the centroid of the section, which would result in high axial compressive strains at the inner face of the tubular section. Only with a low percentage of vertical reinforcement, small axial compression, and a shell thickness of more than 15% of the section's outer diameter, a considerable ductility could be achieved. The test results also show that before the onset of crushing, at the inner face of the tubular section 0.8% of the strain could be observed. The recommendation that the wall thickness should exceed 15% of the section diameter appeared overly conservative since it implied an effective D/t ratio of not greater than 6. However, the remaining conclusions were encouraging for RC chimney sections which typically possess low axial stress ratios and small longitudinal steel ratios.

J. L. Wilson [39] in 2002 investigated the ductility of typical RC chimneys experimentally under cyclic loading. Four hollow circular RC specimens of typical of 4.565m and outside diameter 1.195m with different steel ratios of 0.93%, 0.36%, o.36% and 1.10% were casted and subjected to quasi-static cyclic load with an increase in the level of ductility as ± 0.75, ± 1, ± 2, and ± 3 etc. The stress ratio fc/fck was maintained as 0.05 with the help of prestress. The D/t ratio was maintained as 3.8, which was considered representative of the RC chimney. He concluded that properly detailed RC chimneys possess some ductility and do not show brittle behaviour. Through the yielding of the tension reinforcement, this ductility can be achieved. The limited ductile design (LDD) approach which is also incorporated into the recommendations of the 2001 edition of CICIND [7] suggests that the amount of earthquake forces can be reduced by taking response reduction factor (R) = 2 if ductile detailing is dopted.

Based on the results of the above experimental study J. L. Wilson [53] in 2003 has developed a discretized inelastic frame model. Total 10 case studies were undertaken to compute the inelastic and elastic response of the RC chimneys (which were designed to achieve reasonable ductility). Total 6 different earthquake ground motions were considered for the study. It was found from this study that the response of all four RC chimneys is inelastic, as all RC chimneys develop plastic hinges over the region of 30% to 80% of its shell.

J. L. Wilson [40] in 2009 checked the ductility of RC circular hollow pipe specimens representing RC chimney with openings for bending and shear critical oriented openings. The size of the opening for bending critical section was 600mm x 600mm and that for shear critical orientation was 600mm x 800mm in both the model chimneys openings were kept 300mm above the base. The test specimens were displaced cyclically during the experiment with the application of quasi-static incremental cyclic load with an increasing drift level of 0.20% after each cycle. The ductile behaviour was observed in the test specimen having no opening, whilst 'limited ductile' behaviour was observed in the test specimens with openings (oriented as bending critical and shear critical), but it is important to note here that 'brittle' behaviour was not observed in these specimens also. A drift in the range of 1.5%–1.9% was observed in almost all specimens. The reason for the limited ductile behaviour in the test specimens is observed because of lesser compressive strains in the region where concrete is unconfined and higher tensile strains in the ductile vertical steel.

Table 2 gives the overview of experimental tests done on the RC chimney considering various parameters.

Table- II: Overview of earlier experimental research work on RC Chimney

Reference	*D* (mm)	*D/t*	f_c / f_{ck}	p_t	*M/DV*	Test (#)
Omote [46]	720	9	0	1.3	1.8	Cyclic (1)
Regan [47]	760	19	0 – 0.07	0.7 – 2.4	2.6 – 3.3	Mono (4)
Schober [48]	1100	11	0 – 0.2	0.4 – 1.6	-	Mono (5)
Morkin [49]	355	7	0.01 – 0.08	0.5 – 1.0	-	Mono (4) Cyclic (4)
Whittaker [50]	750	7 – 15	0.25 – 0.42	2.3 – 2.9	4.3 – 4.6	Cyclic (6)
Zahn [51]	325	3 – 6	0.08 – 0.4	2.6	5	Cyclic (6)
Wilson [52]	1194	40	0.05	0.25 – 0.93	3.8	Cyclic (4)
Wilson [74]	1194	40	0.05	0.25 – 0.93	3.8	Cyclic (4) (With opening)

Where,

D = the outer diameter of the test specimen

t = the thickness of the test specimen

f_c = stress generated in the section due to axial compression

f_{ck} = characteristic compressive strength of concrete

M/DV = shear span ratio

P_t = percentage of steel

III. SCALING OF RC CHIMNEY FOR EXPERIMENTAL STUDY

Based on the above study of literature regarding the experimental study on RC chimney and the various already well-established design recommendations from various design standards the chimney can be scaled up for experimental study by using all the laws of similitude [41, 42, 43, and 44] such that the behaviour of the test specimen during the experiment represents the behaviour of actual chimney in the field and thus aiding the results of the experimental work can be to be directly scaled.

For experimental study three independent scale factors are required to be selected, namely geometric similarity, similarity in material properties and equivalent stress level. Tables 3 and 4 respectively show the range in which the geometrical properties and stress level of the test specimens to be selected for scaling up the RC chimney so that the test specimen could follow all the laws of similitude.

Table- III: Key Geometrical Parameters

Parameter	Prototype
D/t	18 – 40
p_t	0.25% – 4.00%
S_t/d_{bv}	7 – 17
S_v/t	1 – 2
St/t	0.5 – 1.0
Cover	$1.5d_{bv}$-$2.5d_{bv}$

Where,
D = the outer diameter of test specimen
t = the thickness of test specimen
d_{bv} = Diameter of vertical reinforcement for test specimen
p_t = Percentage of vertical reinforcement for test specimen
S_v = Spacing of vertical reinforcement for test specimen
d_{bc} = Diameter of transverse reinforcement for test specimen
S_t = Spacing of transverse reinforcement for test specimen

Table- IV: Key Loading Parameters

Parameter	Prototype
Shear Span Ratio (M/DV)	3 – 5
Axial Stress Ratio (f_c /f_{ck})	0.03 to 0.08

To maintain the above axial stress ratio an axial load should be given to the test specimen either through prestressing or through loading jack and the applied force should be maintained and hence monitored throughout the test.

Ideally, for RC models it is advantageous to use a steel reinforcement and a concrete mix with the same or very similar properties to that used in the prototype. In particular, ductility characteristics and ultimate strains of the reinforcing steel should be similar for the model and prototype. Model concrete should possess the same stress-strain characteristics as the prototype concrete, including the same characteristics of compression (crushing) and tensile (cracking) strengths as well as the bond strength. The use of micro concrete requires a careful full mix design, since increasing the proportion of fine aggregate, increases the aggregate/cement contact area and consequently increases the tensile capacity and modifies both the bond characteristics and crack patterns of the model concrete. For such a thin-walled section a typical concrete mix can be prepared with the maximum size of aggregate as 10mm for better concreting of pipe and to avoid the problems related to the use of micro concrete and to guarantee meaningful outcomes.

Also, it is to be noted that the conventional casting process for such a thin-walled hollow circular RC test specimen could result in a minimum thickness of 50 mm of the shell of the test specimen and also the process could be very tedious and time consuming. To avoid the above problem the test specimen could be constructed with the process through which the Hume pipes are casted by maintaining the low speed of rotation.

IV. CHECKING OF TEST SPECIMEN BEFORE APPLICATION OF AXIAL LOAD

Before application of axial and testing under horizontal load, the test specimen should be checked for local bucking, cracking strength of concrete and anti-buckling of reinforcement.

4.1 Local Shell Buckling

A thin-walled tube subject to axial stresses may experience local buckling, which is also referred to as secondary flexure, crinkling, wrinkling, and 'elephant's foot' buckling. Lorenz. R [45] developed a classical expression for shell buckling in 1908, which indicated that the critical axial stress (f_{cr}) was dependent on the elastic modulus (E) and the ratio of the test specimen's thickness (t) to the radius (R) and independent of the cylinder length and can be calculated by following formula:

$$f_{cr} = 0.6 \times E \times t / R \tag{1}$$

Experimental tests indicated that the actual buckling stress was in the order of 0.2 – 0.3 times that given by the classical theory, due to local imperfections and the nonlinear nature of the buckling process [46]. More refined expressions for the critical buckling stress have been developed which relate f_{cr} to the amplitude and half-wavelength imperfection. However, a simpler and lower bound estimate for f_{cr} can be estimated from

$$f_{cr} = 0.12 \times E \times t / R \tag{2}$$

4.2 Tensile or Cracking Strength of Concrete

The tensile strength of concrete is highly variable and dependent on whether the concrete is subjected to direct tension or flexural tension. To calculate the tensile capacity of concrete, the flexural strength of concrete has been used and calculated using different standards as follows:

As per IS: 4998 – 2015 [1], Flexural Tension

$$f'_t = 0.7 \times \sqrt{f_{ck}} \tag{3}$$

As per ACI 318 – 14 [7], Flexural Tension

$$f'_t = 7.5 \times \sqrt{f_c} \tag{4}$$

Where,
f_{ck} = characteristic compressive stress of concrete as per IS: 456 – 2000 [2]
f'_c = specified compressive strength of concrete as per ACI 318 – 14 [7]

But the tensile stress state developed across the thickness of thin-walled circular pipe under flexural action is more representative of direct tension (constant stress) rather than flexural tension (stress gradient). Consequently, the following average concrete tensile strength can be used for chimney-type structures.

4.3 Anti-Buckling Reinforcement

Out of the two main functions of transverse (hoop) reinforcement in a circular member is to some restraint against buckling of the longitudinal reinforcement. Transverse reinforcement is also required for preventing the longitudinal steel from buckling. Mander demonstrated that the compressive stress–strain curve was similar to the tensile curve provided that adequate lateral restrain is provided to longitudinal reinforcement. [50] The theoretical buckling stress may be calculated using Euler's theory:

$$f_{cb} = \pi^2 E/(I/r)^2 \tag{5}$$

Where,
f_{cb} = Critical buckling stress
E = Tangent modulus of elasticity
r = Radius of gyration = 0.25 x reinforcement steel bar diameter
l = Effective length

The longitudinal steel would need to deform in double curvature between the transverse reinforcement assuming that the reinforcement steel could only buckle outwards once the concrete cover had spelled. [51] The longitudinal reinforcement is therefore effectively fixed between the transverse reinforcement spaced at S_c, resulting in an effective length of l = 0.5S_c. Consequently, the ratio of transverse reinforcement spacing to longitudinal reinforcement diameter can be expressed as follows:

$$S_c / d = 1.5\left[E / f_{cb}\right]^{0.5} \tag{6}$$

For ductile behaviour, the critical buckling stress should at least be equal to yield stress, and hence the S_c/d ratios are dependent on the tangent modulus of steel which varies significantly from elastic to the plastic range.

V. CONCLUSION

paper deals with a review of the various literature available for analytical and design procedures for the RC chimneys. The paper also discusses the experimental work that has been carried out by various researchers in this field. Based on their work, various geometrical parameters, loading parameters and material properties to be maintained for the test specimen for experimental work have also been discussed here. For the analysis of such tall slender cantilever structural configuration and subjected to the large temperature gradient, wind loads including static and dynamic effects or earthquake loads, temperature load and dead load including self-weight and weight of lining shall be considered. Although it was observed during the study that in most of the cases in comparison with the earthquake force, the wind force is the governing force and to stimulate the wind force monotonic load can be applied on the test specimen when the strength of the test specimen is a concern.

It can be concluded from the study that all the laws of similitude have to be maintained during the test in form of geometry, material and load so that the behaviour of the test specimen can represent the behaviour of the prototype in the field. Also before application of axial load to maintain the loading parameter check for buckling of the shell of test specimen and buckling of the reinforcement should be carried out.

In casting use of micro concreting should be avoided also use of 20mm size of aggregate may result in honeycombing and hence it would be preferable to use 10mm size of aggregate as the maximum size of aggregate in the concrete mix design.

Instead of the conventional method of casting, the casting technique Hume pipe can be used because the conventional method of casting will result in a minimum thickness of 50 mm and hence to maintain the D/t ratio diameter of the test specimen needs to be increased which may result in to increase in overall size and weight of the test specimen which may be difficult to handle during the placing, lifting and testing of the test specimen. The reinforcement must represent the ductility of the actual reinforcement to be used in the prototype. Axial load that represents the self-weight of the chimney can be applied through prestressing. Finally, the tests on chimneys help to identify the performance of the RC chimney under different load conditions, which is used by researchers and industries to design the new best RC chimneys with low earthquake and wind load effects and to compare the results with design recommendations given in various design codes related to RC chimney design.

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