Experimental Study on RC Chimneys – A State of Art

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Abstract— Tall RC chimneys are tubular in section and tapered or un-tapered along its height that convey polluted gases to a higher altitude where the dilution occurs and hence, bring the concentration within acceptable limits for breathing when it reaches lower altitude. The predominant loading to be considered in the design of the RC chimneys is the wind force which is generally more critical than earthquake force. The bending moment induced by the wind load on the lower section interacts with axial compression due to dead load. There is significant difference in the design criteria given in various design codes. Hence, it becomes necessary to carry out the detailed comparative study of some prevailing design codes for chimneys and to compare these results with the outcomes of experimental study to identify the design methodology that closely represents the behaviour of RC chimney.

Key words: RC Chimneys

I. INTRODUCTION

Chimneys can be defined as hollow, tall, and slender vertical structures built to serve the purpose of carrying smoke away to higher altitude; so that when its concentration reaches lower altitude after dilution due to atmospheric turbulence, it is within the acceptable limits for breathing.

II. LITERATURE REVIEW

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Quasi-static cyclic tests were carried by Omote Y and Tekada T in 1975 on a RC chimney test specimen of length 5.0m, external diameter 800mm and thickness 80mm.The test specimen consisted of 1.3% of vertical steel bars placed in the centre of the wall and it was not subjected to axial load. The setup included a simple beam on which a two-point transverse cyclic loading with a constant moment over the central 2.0m region was applied. The specimen displayed remarkable hysteretic behaviour. Even though this test is beneficial, its results cannot be directly implemented or compared to actual reinforced concrete chimneys as most of them have a D/t ratio considerably more than 10 and also they undergo simultaneous actions of axial force and bending moment.

Regan in 1981 examined four test specimens with an outer diameter of 800mm, shell thickness of 40mm and cantilever length of 2.5m for specimen 1; and 2.0m for others. Through a saddle mechanism, monotonic loading was imposed at the top. With the help of prestressing wires, axial stress ratio (fca/fck) between 0 to 0.08 was introduced in the test specimens. Vertical reinforcement ratio was kept in the range of 0.7% to 2.4% and a mesh was placed on either of the faces of the thin-walled cylinder (1.0%). At the place of the welds, the brittle wire mesh failed when the strain had only reached 0.8%. Except test specimen 3, the remaining specimens (i.e., 1, 2 and 4) consisted of shear reinforcement of about 0.5%. Instead of normal concrete mix, micro-concrete was used to generate thin-walled section. Relatively, large shear forces and low shear span ratios i.e., 3.3 for specimen 1, and 2.6 for the others were observed. Other than specimen 2, the remaining specimens showed flexural mode of failure; that originated by fracturing of the mesh in the tension at lower strains followed by spalling of concrete in the compression. As the concrete was not properly confined on either of the sides; when subjected to a uniform compressive stress, the thin-walled sections were found to be brittle. The use of brittle mesh (for vertical as well as shear reinforcement) hugely influenced the outcomes of the research by Regan. Due to the rupture of vertical reinforcement (at lower strain), a sudden increase occurred in the tensile and compressive strains i.e., the curvature; because of which widening and extension of the cracks beyond the tension zone along the periphery was observed. The tensile strains due to the rupture of the vertical reinforcements caused the concrete to spall in the compression zone and had this tensile strain been limited by yielding, this spalling would not have taken place. As the brittle failure mode was developed by the introduction of brittle steel (vertical as well as shear), its use must be discouraged in such tests.

An experimental research was carried out by Schober H and Schlaich J in 1984 on five test specimens, each of 5m length, external diameter of 1200mm and a comparatively large wall thickness of 100mm. The centrally placed tendons were used to apply axial force through which an axial stress ratio (fca/fck) ranging from 0.00 to 0.20 was maintained for each test specimen. Vertical reinforcement ratios between 0.45% to 1.64% were maintained by reinforcing the test specimen with one layer of 10mm HYSD bars. Until failure, monotonic loading was applied to maintain a constant bending moment and so, the influence of shear-flexure was not considered. The experiments indicated that for determining the deformations, it is needed to consider the stiffness of concrete in the tension region between the cracks. Although, the results obtained were satisfactory with respect to the test objectives, they were not very useful interms of understanding the inelastic cyclic behaviour of typical chimney sections. Due to the small D/t ratio, the absence of shear force and monotonic loading, the results of the study cannot be extrapolated to understand the behaviour of RC chimney in earthquake.

Ultimate capacity (strength and stiffness) of RC hollow circular sections under axial and transverse loads were experimentally determined by Mokrin and Rumman in 1985. The outcomes of the experimental research work were also compared with the available theoretical results. Out of total eight test specimens, four were monotonically loaded and the rest were cyclically loaded up to failure. Specimen properties were as listed; 3.25m long, 406mm external diameter, wall thickness 50mm and with one layer of reinforcement placed in the centre of the wall. The range of longitudinal reinforcement ratio was maintained from0.5% to 1.0%, and the specimens were imposed to an axial load using prestressing cables to produce an axial stress ratio (fca/fck) from 0.00 to 0.08. The specimen was tested as a simply supported beam and a two-point loading (with 1.0m gap) at centre of the specimen was applied. As a result, it underwent only a constant maximum moment i.e., no shear. This setup was not truly a representative of chimneys which are cantilever in true sense. The outcomes of the study showed that the ultimate capacity of the specimen is directly proportional to the reinforcement ratio and/or axial load, irrespective of the load history. The test specimens would show larger ultimate capacities when subjected to cyclic load with gradually increasing peaks rather than that subjected to monotonic load. For practical purposes, the monotonic analysis can be used to predict the ultimate strength of the sections subjected to gradually increasing cyclic loading. The moment-curvature interaction curves for test specimens subjected to monotonic load can be plotted using three separate break points: (i) at the first tension crack (ii) at yield and (iii) at failure. Good hysteresis behavior of the specimens under cyclic loading was interpreted using plotted moment-curvature diagrams, yet failure modes as well as development of plastic hinges were not studied. In this case also, due to the lower D/t ratios, the results could not be confidently applied to the chimneys that have higher D/t ratios inspite of using realistic vertical steel ratios and axial stress ratios in experiment.

A detailed experimental study was taken up by Whittaker D in 1988 to demonstrate the behaviour of the legs of offshore RC gravity platforms in earthquake. Six specimens of length 3.2m, external diameter 800mm and a thickness of 100mm for two of the test units and 50mm for the rest, were casted as cantilevers and tested under quasi-static cyclic loading imposed at the free end. An external actuator was used to apply axial loads to maintain the axial stress ratios (fca/fck) varying from 0.25 to 0.42.The use of HYSD steel bars of 6mm and 10mm diameter maintained the vertical reinforcement ratios ranging from 2.3% to 2.9%. Square ties acting as shear reinforcement throughout the thickness of the specimen were provided in order to ensure the confinement of concrete as well as to avoid the buckling of the vertical reinforcement. The experiments indicated the ductile behaviour of the sections subjected to higher axial loads and vertical reinforcement ratios, provided that close ties i.e., sufficient confinement and anti-buckling steel was present to prevent the occurrence of brittle compression modes of failure. The tests were thoroughly undertaken and can surely be considered to be directly relevant to offshore gravity platforms, yet its results cannot be directly applicable to RC chimney due to the introduction of confining reinforcement and the use of different loading parameters, sectional geometry and percentage of steel.

F. A. Zahn, R. Park and M. J. N. Priestley in 1990 assessed six hollow cylinders in pairs of two, with length 3.1m and external diameter 400mm each but the thickness of 94mm, 75mm and 55mm resulted in lower D/t ratios of 3.2, 4.3 and 6.3. The cylinders were tested as simply supported beams subjected to transverse loading through solid diaphragm located in the centre of the specimen. The aim of the experiments was to assess the ductility of the hollow circular sections with one layer of confinement steel i.e., circular spiral reinforcement placed near the outside face of the wall. All cylinders consisted of a high vertical reinforcement ratio of 2.6% and a hoop reinforcement ratio of either 1.1% or 1.4%. The axial stress ratio (fca/fck) ranging between from 0.08 to 0.40 was maintained using axial load applied through jacks. The research work revealed that the neutral axis depth at the flexural capacity significantly impacted the available curvature ductility of the column. Had the neutral axis been near to the unconfined internal face of the specimen, resulting in lower longitudinal compressive strain, then ductile behaviour could be expected. Whereas if the neutral axis was at some distance from the inside face and towards the centroid of the section, then the high axial compressive strains at the inside face would cause brittle behaviour. Significant ductility could only be obtained at lower axial loading, smaller vertical reinforcement ratio and a shell thickness not less than 15% of the overall diameter of the section. Further, the experiments conducted showed that 0.8% strain could be developed at the internal face of the specimen wall before the onset of crushing. The conclusion of the study which recommended that shell thickness should not be less than 15% of the outer diameter seems to be overly conservative as it would result in an effective D/t ratio less than 6. Inspite of this, the other results could still be relevant to typical RC chimney sections that have lower axial stress ratios and smaller vertical reinforcement ratios.

In 2002 J. L. Wilson undertook an experiment to study the ductility of typical RC chimneys subject to cyclic loading. Four cylindrical RC specimens typical of length 4.565m and external diameter 1.195m with different steel ratios of 0.93%, 0.36%, and 1.10% were constructed and tested under quasi static cyclic load. These specimens were cyclically displaced to increasing ductility levels of± 0.75, ± 1, ± 2, and ± 3 etc. The stress ratio (fca/fck) was kept at 0.05 using prestress. The D/t ratio of 3.8 (representative of typical RC chimney) was maintained. The study concluded that if the RC chimneys are well-detailed with reinforcement, they will not show brittle and would also possess some ductility incorporated via yielding of the steel in tension. The important conclusion of the study is the recommendation of the value 2 for response reduction factor in earthquake analysis of RC chimneys when ductile detailing is provided. Based on the outcomes of the above-mentioned experimental work, J. L. Wilson [26] in 2003 had developed a discretized inelastic frame model for analysis of RC chimneys under earthquake. With the developed analytical model, the inelastic and elastic response of 10 realistic chimneys (designed for moderate ductility) were studied for six different earthquake ground motions. This analytical study concluded that the RC chimney develops a number of plastic hinges in the shell before undergoing failure, which is an indication of inelastic behaviour. The response seemed to be dominant in the higher modes with considerable inelastic deformations mainly concentrated over the region between 30–80% of the chimney windshield.

In 2009, J. L. Wilson examined the ductility of cylindrical test specimens representing RC chimneys with openings. The orientation of the opening was kept bending critical in one test cylinder and was kept shear critical in the other test cylinder. The size of bending critical oriented opening was 600mm x 600mm and that of shear critical oriented opening was 600mm x 800mm.In each of the chimney specimen, openings were located 300mm above the model foundation. The loading procedure (transverse loading) used for testing the test cylinders was quasi-static cyclic loading. The specimens were cyclically displaced to increasing drift level of 0.20% at each cycle. Specimen 1 with no opening displayed 'ductile' behaviour, whilst specimen 2 and specimen 3 with openings showed 'limited ductile' behaviour, but essentially not 'brittle' behaviour'. A drift in the range of1.5%–1.9% was attained by all the test specimens. Lower compressive strains in the unconfined concrete zone and higher tensile strains in the longitudinal (ductile) reinforcement caused all the test specimens to behave in a limited ductile manner.

III. CONCLUSION

Earlier experimental research and studies have been conducted to examine this behaviour of hollow RC tubes under cyclic and monotonic loading, but very few experimental research work has been carried out previously on the test specimens that represent actual RC chimney configurations and hence, results of the same do not exactly represent the behaviour of the RC chimney.
Further, openings are an essential part of the chimneys and chimneys with openings are critical under lateral loading. But the only research work that has been carried out on the test specimens that represent actual chimney configuration with opening is under cyclic loading.

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