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CODE RECOMMENDATONS FOR THE ASEISMIC DESIGN OF TALL REINFORCED CONCRETE CHIMNEYS

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SUMMARY

This paper presents results of recent experimental tests which indicate that reinforced concrete chimneys possess some ductilty when subject to cyclic loads. Based on these tests an inelastic procedure has been established for assessing the performance of reinforced concrete chimneys subject to severe earthquake ground shaking. This procedure has been used to; analyse a number of chimneys, develop design recommendations and establish appropriate ductility factors. In addition, a 245 metre tall chimney designed using these recommendations is compared on a cost and performance basis with designs undertaken using a number of International chimney codes of practice.

INTRODUCTION

The behaviour of tall reinforced concrete chimneys subject to earthquake excitation is not well understood and consequently codes of practice around the world provide conservative aseismic design guidelines. (Ref 1-2).

Codes of practice for structures generally recognise that it is not economical to design structures to remain elastic at the ultimate earthquake event and generally allow some inelastic behaviour. A commonly accepted measure of the energy absorption capacity of a structure is the ductility factor which is the ratio of the displacement of the structure at failure to the displacement at first yield. Most codes specify the response spectrum method for calculating the magnitude and distribution of earthquake induced forces in reinforced concrete chimneys. The key parameters associated with the earthquake analysis and the design response spectrum (DRS) specified in codes of practice are in the form: DRS=(aCS)*(IF)*(LF/R). The factor (aCS) defines the elastic response spectum representative of the site whilst the importance factor (IF) effectively modifies the return period of the design earthquake event from the standard 475 year return period (ie. 10% exceedance in 50 years). The effective ductility factor (R/LF) modifies the elastic spectrum for inelastic response (R = structural response factor, LF = load factor). The ductility factor specified by codes for chimneys has historically been significantly less than those for normal building structures in the belief that chimneys were brittle with little redundancy and the failure of one plastic hinge could cause collapse .

The degree of ductility permitted in concrete chimneys by codes of practice varies widely (Ref. 6). CICIND (Ref. 1) and ACI307 (Ref. 2) assume tall reinforced concrete chimneys are brittle with an effective ductility factor of 0.7 for a 1 in 475 year return period earthquake event . UBC (Ref. 3, 4) specifies a nominal ductility factor of 2.9 for chimneys but also specifies a minimum base shear force, which effectively makes the factor site and natural period dependent and hence substantially reduces the value for most tall chimneys. Although the draft EC8 standard (Ref. 5) specifies a maximum ductility factor of 3 the introduction of capacity design clauses, overstrength factors and rotational response spectra substantially reduces this value.

The adoption of a small ductility value tends to make reinforced concrete chimneys uneconomical in areas of high seismicity. The designer should also be aware that the greater the inelastic demand, the greater the overall

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damage potential at the ultimate event. The ductility value selected should be consistent with the owners requirements and consistent with the aseismic design philosophy of the other components of the facility.

This paper presents results from an experimental study undertaken to investigate the ductility of typical reinforced concrete chimney sections under cyclic loading. Based on these experimental results an inelastic analysis procedure has been established for assessing the performance of reinforced chimney structures under extreme earthquake excitation. This procedure has been used to analyse a number of chimneys and to develop design recommendations and establish appropriate ductility factors. In addition, a 245 metre tall chimney designed using these recommendations is compared on a cost and performance basis with designs undertaken using the CICIND, ACI307, UBC and EC8-3 codes of practice.

2. EXPERIMENTAL RESULTS

Four reinforced concrete pipes of length 4565mm, diameter 1200mm, thickness 30mm, with an axial stress 0.05MPa and possessing 1.0%, 0.25%, 0.25% and 0.85% effective longitudinal reinforcement ratios (standardised to a yield stress of 400MPa) have been fabricated and tested as horizontal cantilevers by applying a cyclic horizontal load at the free end. All pipes behaved in a ductile manner as demonstated in Figure 1 which plots the final hysteresis loop of lateral force versus displacement for each of the four cyclic tests. In addition, the lateral force versus displacement is shown in Figure 2 for all cycles of Test 4 (0.85% reinforcement ratio).

The hysteresis shape was stable with increasing displacements resulting in an increase in the bending moments associated with the strain hardening of the reinforcement. The reduction in stiffness associated with an increase in ductility is characteristic of the closure of wide cracks, softening of the concrete matrix and the softening of the reinforcement due to the “Bauschinger” effect. The pinched shape of the hysteresis loops is common for members with low axial loads. This ductile behaviour was achieved through yielding of the reinforcement in tension rather than non linear compressive behaviour of the concrete as demonstrated in Figure 3.

The failure of the pipes was initiated by the longitudinal steel buckling due to the reduced EI value from the Bauschinger effect combined with the loss of the concrete cover through progressive deformation in the vicinity of the circumferential cracks as the concrete was cycled back and forth from extreme tension to compression.During the tests the pipe developed a plastic hinge with a length in the order of 0.2D to 0.3D $\left[0.05 M/V \; to \; 0.075 M/V\right]$ characterised by a series of severe circumferential cracks.

3. INELASTIC EARTHQUAKE ANALYSES

The results from these experimental tests which demonstate that typical reinforced concrete chimney sections are not brittle but possess some ductility have been used to develop an inelastic finite element model (with lumped plastic hinges) to estimate the post yield behaviour of tall reinforced concrete chimneys. The modelling procedure (which is described in Ref. 10) has been used to study the failure mode of tall chimneys and to estimate the ratio of the failure level to the elastic level earthquake peak effective ground acceleration.

A 245 metre tapered reinforced concrete chimney with an outside diameter varying between 16.8m and 26.0m and a thickness varying from 0.35m to 0.70m was designed to resist eathquake induced forces described by the 1994 UBC (Ref. 3) soft soil response spectrum .

An acceleration coefficient of 0.15g corresponding to the 475 year return period was selected to represent a region of moderate seismicity. The chimney was designed in accordance with the CICIND recommendations assuming elastic behaviour and uncracked properties. The application of the 1.4 load factor (LF=1.4) increased the nominal elastic design earthquake to a_e=0.21g. The chimney was then analysed inelastically using an ensemble of synthetic earthquakes compatible with the design response spectrum. The earthquakes were scaled until the curvature ductility demand exceeded the capacity at one of the plastic hinges, at which the chimney was deemed to have failed. This event corresponded to a failure acceleration of a_f=0.7g for this case study chimney.

The study (which is descibed in detail in Ref. 10) has highlighted the complex dynamic response of a typical tall reinforced concrete chimney under earthquake excitation. The structure can be thought of as a highly tuned profiled cantilever which is "whippy" in nature and dominated by higher mode effects. The behaviour of such a structure cannot be readily predicted using a simple static push over analysis nor by a simple single degree of freedom substitute structure.

A cost effective option for the design of chimneys to resist earthquakes is to limit the maximum moments that can be developed in the chimney by encouraging the development of multiple plastic hinges rather than a single plastic hinge. Multiple plastic hinges have the advantage that the curvature ductility demand will be spread over a wide region of the chimney to dissipate the seismic energy. Chimneys inherently will possess a reasonable curvature ductility capacity at all plastic hinge locations and consequently develop some global ductility provided that they are designed and detailed for ductility using some simplified capacity design principles.

The detailed analyses carried out for the 245metre tall chimney were repeated for a further six chimneys ranging in height from 115m to 189m. The results suggest that the ratio of failure acceleration to elastic acceleration exceeds 4 ($a_f/a_e>4$) provided that the chimney has been designed and detailed so that the curvature ductility capacity (based on a yield curvature defined by 0.5 EI_g) exceeds 10 at the critical sections. Design recommendations to achieve this criterion, such as limiting the axial stress ratio and limiting the longitudinal reinforcement ratio are discussed in the next section. In addition, design methods for reducing earthquake loads by accounting for ductility are discussed.

4.0 CODE RECOMMENDATIONS

The seismic design approach recommended in this paper is based on a dual performance based design philosophy: (a) designing the chimney elastically to resist earthquake induced loads considered reasonable for a damageability limit state earthquake event and (b) designing the chimney with sufficient ductility so that the chimney will survive an extreme earthquake event without premature failure and collapse. An importance factor of IF = 1.4 is recommended for important chimneys and a load failure of LF = 1.0 is recommend for the ultimate limit state.

It is recommended that the seismic actions be calculated using the response spectrum method assuming uncracked properties with a structural response factor (R factor) dependent on the level of seismic detailing specified : R = 1.0 (no specific seismic detailing) and R = 2.0 (capacity design and seismic detailing)

The design of the chimney should be consistent with the principles of capacity design. The foundation system and the shell in the vicinity of openings should be designed for overstrength (flexure and shear) so that inelastic flexural behaviour will develop in the ductile regions of the shell away from significant openings.

Specific detailing requirements include: (a) use of high ductility reinforcement steel, (b) introduction of staggered splices, (c) specification of sufficient longitudinal reinforcement to ensure that the ultimate moment capacity of the chimney at any cross section is greater than the nominal cracking strength and (d) limiting the ratio of the axial stress to ultimate concrete compressive strength to 10% and (e) limiting the longitudinal reinforcement ratio to 1.5% in regions where plastic hinges could form to ensure adequate overall ductility.

5. COMPARISON WITH OTHER CODES OF PRACTICE

This section summarises the cost and performance of a 245 metre tall power station chimney (deemed an important structure) designed using the recommendations of Section 4 with designs undertaken using the following codes of practice: CICIND, ACI307, UBC and EC8-3. The soft soil response spectrum previously described was used to provide an onerous and consistent basis for the elastic response spectrum for each of the designs. An acceleration coefficient corresponding to the 475 year return period of a = 0.30g was selected to reflect a region of relatively high seismicity.

The seismic design approach recommended in CICIND and ACI307 encourages elastic behaviour with no requirements for ductility. The nominal elastic design earthquake (which results in the ultimate bending moments being developed in the windshield) is effectively a_e = 0.42g (LF = 1.4, IF = 1.0, and R = 1.0) for both codes, with an associated windshield cost in the order of US$3.0 million. Significantly the chimney was designed elastically without consideration to the likely mode of failure, and consequently under extreme ground shaking the chimney may fail in a brittle and catastrophic manner around the openings or in the foundation system.

UBC-97 allows the earthquake forces to be reduced for ductility through the introduction of a ductility factor, without specifying any special design and detailing requirements. Further, the ëRí factor recommended is both site and natural period dependent and consequently does not appear to have a totally rational basis. The nominal elastic design earthquake associated with the UBC design is a_e = 0.21g (LF=1.0, IF = 1.0 and R = 1.5) with an associated windshield cost of US$2.2 million.

EC8 - 3 recommends the chimney be designed to encourage ductility through the formation of one plastic hinge using capacity design principles. The overstrength factors recommended are considered by the author to be non-conservative due to higher mode effects significantly magnifying the chimney response. The nominal elastic design earthquake specified at the hinge is effectively a_e = 0.14g (IF = 1.4, R = 3) and a_e = 0.21g (LF = 1.0, IF = 1.4 and R = 2) away from the hinge resulting in a windshield costing in the order of US$2.1 million. However, if the overstrength factors are increased to account for the higher mode effects then the cost increases to US$2.6 million. In addition the concentration of the damage and inelastic behaviour at one location has further design, detailing, construction and cost implications.

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The limited ductility design approach outlined in Section 4 of this paper is the most cost effective aseismic design strategy and allows the earthquake forces to be reduced for ductility by encouraging the formation of multiple plastic hinges in the windshield away from the openings and foundation system. The development of multiple plastic hinges has the advantage that the inelastic behaviour and curvature demand will be spread over a wider region of the chimney to dissipate the seismic energy, and will limit the seismic forces that are transmitted to the foundation system. The associated nominal elastic earthquake is a_e = 0.21g (LF = 1.0, IF = 1.4 and R = 2) with a failure acceleration in excess of a_f = 0.70g, and a windshield cost in the order of US$2.2 million.

6.0 CONCLUSIONS

1. Well detailed reinforced concrete chimneys are not brittle and possess some ductility developed through yielding of the reinforcement in tension.

2. Tall reinforced concrete chimneys being highly tuned, profiled cantilevers respond in a complex manner to earthquake excitation, with the response dominated by higher mode effects, in both the elastic and inelastic range.

3. Seimic design and detailing recommendations have been outlined in section 4.3 of this paper to encourage limited ductile rather than brittle behaviour through the formation of multiple plastic hinges in the windshield away from openings to dissipate the seismic energy and minimize the induced seismic forces.

4. Elastic seismic forces corresponding to the 1 in 475 year event may be reduced by a structural response factor R=2 provided that the chimney has been designed in accordance with the seismic design and detailing recommendations.

5. The seismic design approach specified in ACI 307 and CICIND encourages elastic behaviour with no requirements nor guarantees for ductility. Consequently a chimney designed following the guidelines will be significantly more expensive and may behave in a brittle manner under an extreme earthquake event.

6. The seismic design recommendations of EC8-3 which encourage ductility through the formation of one plastic hinge using capacity design principles are considered non conservative due to higher mode effects magnifying the chimney response. Significantly larger over strength factors that those currently specified are needed in the upper section of the chimney with resulting design and cost implications. The concentration of the damage and inelastic behaviour at one location has further design, construction and cost implications.

7. The seismic design approach recommended in UBC allows a reduction in the elastic forces for ductility without specifying any special design and detailing requirements. Consequently a ductile response of the chimney under extreme earthquake excitation cannot be guaranteed. Further, the R factor recommended in the UBC being both site and natural period dependent does not appear to have a totally rational basis.

7.0 ACKNOWLEDGEMENTS

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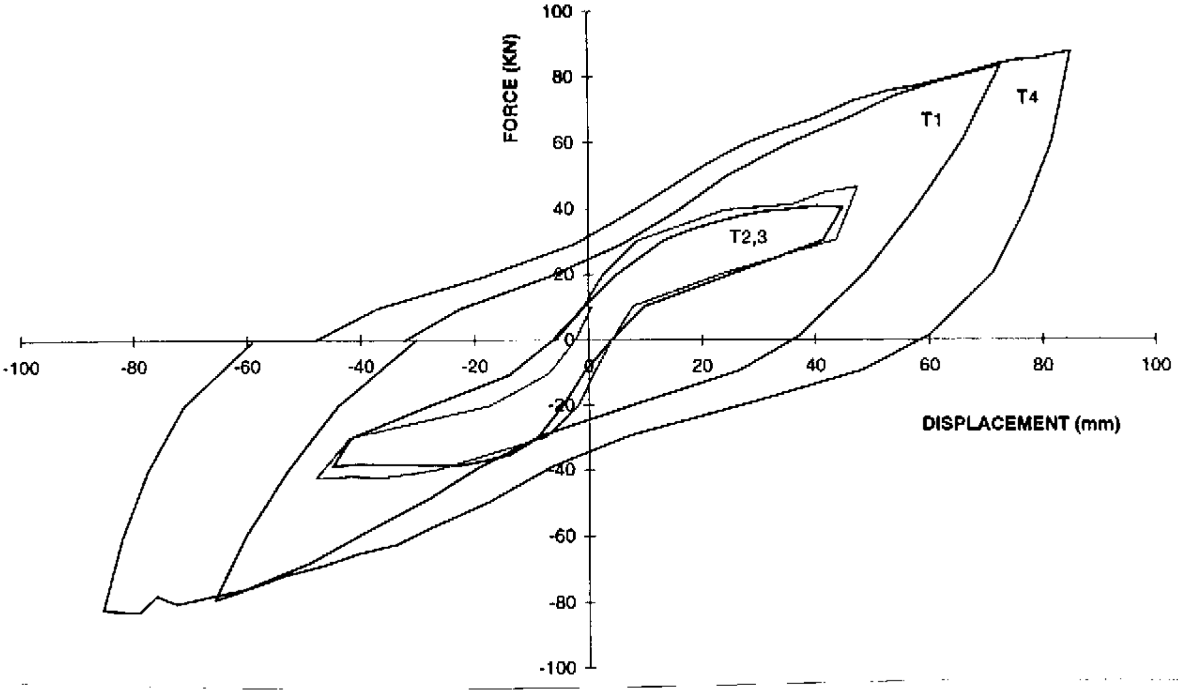

Figure 1 - Lateral force versus displacement
(Tests 1,2,3,4)

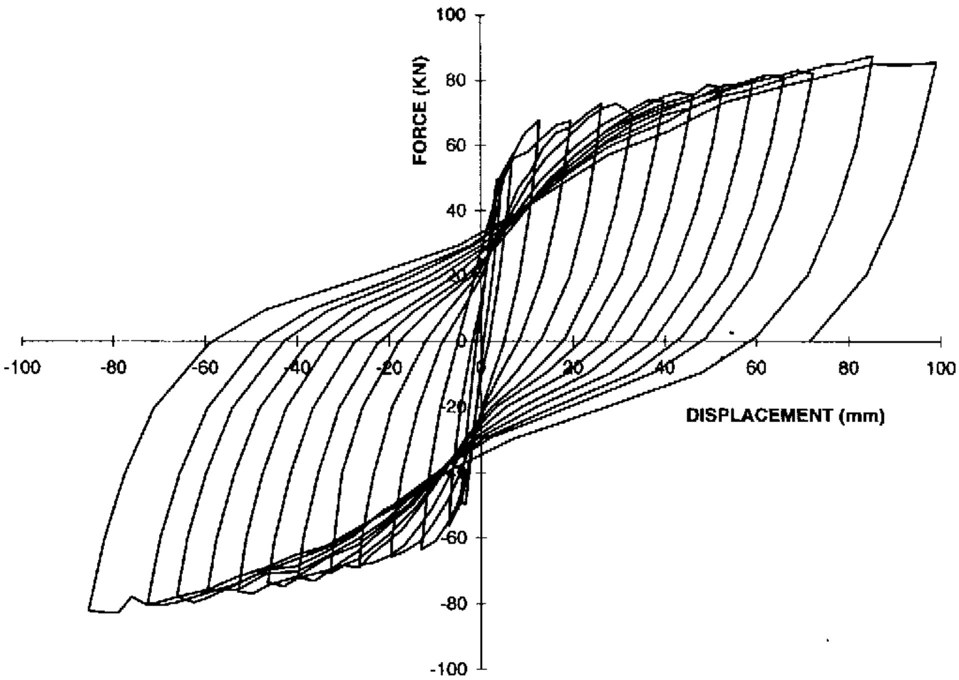

Figure 2 - Lateral force versus displacement
(Test 4 - 0.85%)

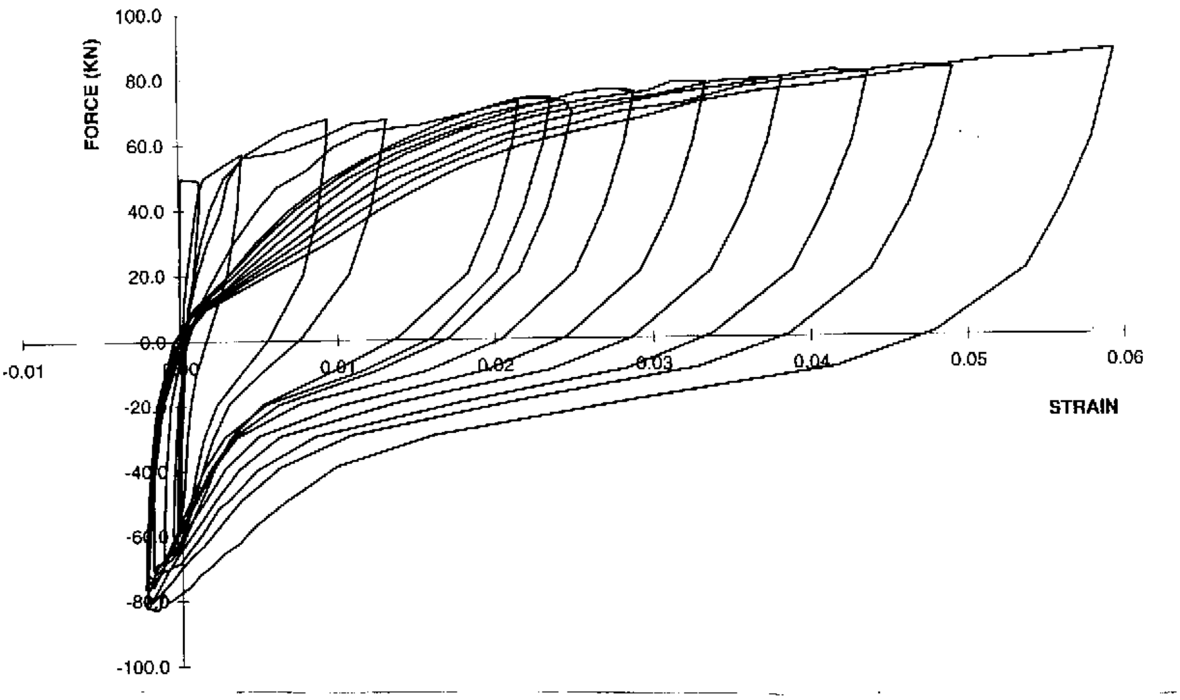

Figure 3. - Lateral force versus average extreme fibre strain (Test 4 - 0.85%)