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Finite Element Modeling of Cyclic Behavior of a Reinforced Concrete Chimney Section

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Abstract

In this study, a numerical model was presented to simulate the experimental behavior obtained for a reinforced concrete chimney section. The purpose of the previous experimental investigation conducted for the chimney section was to evaluate the effect of large openings on the cyclic response in order to reveal the performance of such structures under seismic loads. A detailed finite element model of the chimney section was constructed and all of the reinforcements of the chimney were directly taken into account by line element representations. The volume of the concrete chimney shell was modeled with hexahedral elements. A bi-linear material model was used for the reinforcements. A crucial step in the finite element approach was to employ a constitutive material model that took the multi-axial state of stress and confinement effects in concrete into account. The Winfrith concrete material model of the commercial LS-Dyna structural code was chosen for the shell of the chimney section. Comparisons of the results of the finite element study with the experimental measurements showed a good agreement for the base moment-displacement response and crack formations around the opening regions of the chimney section.

Keywords: Reinforced concrete chimneys, Cyclic loading, Finite element model, Concrete material model

Betonarme Baca Kesitinin Tekrarlı Yükleme Altındaki Davranışının Sonlu Elemanlar Metodu ile Modellenmesi

Öz

Bu çalışmada, betonarme bir baca kesitinin deneysel davranışına benzer sonuç verebilecek bir sayısal model sunuldu. Daha önce yapılmış olan deneysel çalışmanın amacı, tekrarlı yüklere maruz kalan ve geniş açıklıkları olan baca tipi yapıların deprem yükleri altındaki performanslarını değerlendirebilmekti. Detaylı bir sonlu elemanlar modeli oluşturuldu ve bütün donatılar direkt olarak çubuk elemanlar ile

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modellendi. Baca kesitinin beton cidarı hacim elemanları ile modellendi. Donatı malzemesi için bilineer bir malzeme modeli kullanıldı. Beton malzemenin çok-eksenli gerilmeler altındaki davranışını ve donatı sargılama etkisini modellemek çalışmada önemli bir adım teşkil etti. Baca kesitinin beton cidarını için ticari bir yapısal çözüm programı olan LS-Dyna'daki Winfrith modeli kullanıldı. Sonlu elemanlar analizinde elde edilen taban momenti-yer değiştirme sonuçları ve betonda oluşan çatlaklar daha önce elde edilen deneysel sonuçlarla karşılaştırıldı.

Anahtar Kelimeler: Betonarme bacalar, Tekrarlı yükleme, Sonlu elemanlar modeli, Beton malzeme modeli

1. INTRODUCTION

The 17 August 1999 Marmara earthquake in Turkey caused the spectacular collapse of a tall reinforced concrete chimney at the Tupras Refinery. The chimney behavior was investigated by various researchers [1,2]. The chimney had a single large opening at one-third of its height from the base. The presence of large openings combined with insufficient opening reinforcement detailing and provisions may significantly reduce the ductility of chimney structures. Experimental investigations play a crucial role in understanding the behavior of chimney sections subjected to load reversals.

The cyclic performance of a reinforced concrete chimney section with two large openings was investigated experimentally by Wilson at the University of Melbourne [3]. The purpose of the experimental investigation was to evaluate the seismic performance of chimney structures with large openings subjected to seismic loads. The analytical work presented in this report was coordinated with the work by Wilson [4]. The objective of the analytical study was to use the test results as a benchmark case such that the analytical methods serve as a tool for future parametric studies that take into account of different loading conditions, material properties, and geometry.

Figure 1 shows the general view of the test setup of the chimney section at the University of Melbourne. A detailed description of the test results was published by Wilson [4].

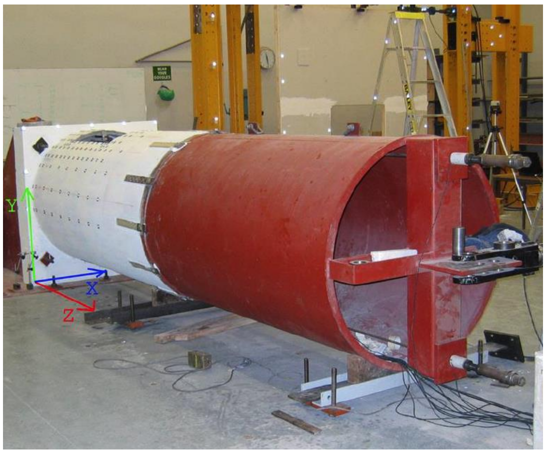

Figure 1. Cyclic loading test setup of the reinforced concrete chimney section at the University of Melbourne [3]

Figure 2 provides the dimensions of the structural components of the experimental setup. Figure 3 shows a close-up view of the two openings that are placed in a diametrically opposite configuration [3].

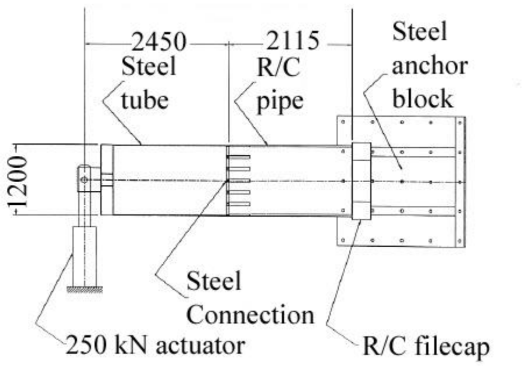

Figure 2. Dimensions of the structural components

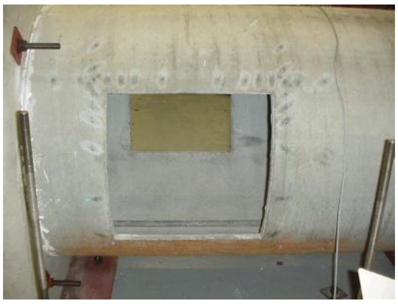

Figure 3. Diametrically opposite large openings of the chimney section [3]

The chimney has a length of 4.6 m and a diameter of 1.2 m. The concrete shell has a constant thickness of 0.04 m along the length. There are two square-shaped openings of size 0.6 m by 0.6 m facing each other located at 0.3 m above the fixed base, as illustrated in Figure 4.

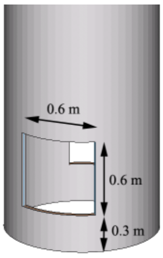

Figure 4. Dimensions of the openings

Figure 5 shows the 5.8 mm diameter rebars used for the longitudinal reinforcement. The rebars are explicitly modeled in LS-Dyna with 2-node line elements. Same diameter rebars were used as additional reinforcement around the openings in a configuration of 3 extra rebars on each side.

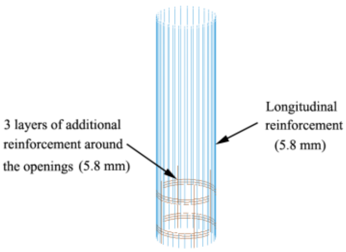

Figure 5. Opening reinforcements and longitudinal rebars of the chimney section

2. METHODOLOGY

In order to capture the nonlinear behavior of the test chimney, the commercial structural solver LS-Dyna was used [5]. LS-Dyna provides capabilities for modeling nonlinear material constitutive relationships, large strains and displacements, and forms the structural equilibrium in the deformed configuration.

The dynamic equation of motion is incorporated into the LS-Dyna program by using an explicit time-integration approach. A central-difference algorithm is used to implement the explicit time integration in LS-Dyna. Eq. 1 gives the formulation of motion in the explicit scheme. The internal and external force vectors in the right hand side of the equation include the damping effects. Using a diagonal mass matrix *M* simplifies the solution significantly for the unknown accelerations. Equilibrium is formed at time step *n* and the unknown displacements can be directly computed without the need of a solution for systems of equations.

$$M \cdot a_n = f_n^{ext} - f_n^{\text{int}} \qquad (1)$$

f_n^{ext} = Vector of external structural forces,

f_n^{int} = Vector of internal structural forces,

M= Mass matrix,

a_n = Acceleration vector.

The advantage of the explicit scheme is the removal of a need for iterations in the analysis [6]. Therefore, complex nonlinear material models can be utilized in the dynamic analysis.

The finite-element results presented in this study are obtained by the explicit time integration scheme used in the LS-Dyna program. In order to model the pseudo-static nature of the chimney test, the loading applied in the finite element model of the chimney was 13.5 seconds in order to avoid significant inertial effects.

Figure 6 shows the imposed axial load at the top section of the chimney in the LS-Dyna analysis.

The axial load of 226 kN was applied in 3 seconds to minimize the dynamic effects.

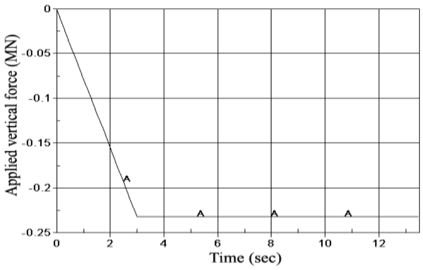

Figure 6. Time variation of the axial pre-stressing load for the chimney section

The cyclic loading applied at the top section of the chimney is shown in Figure 7. The duration of each push-pull cycle was 2 seconds. The imposed displacements for the last 3 cycles are 51, 68 and 85 mm, respectively. The loading ended at a time instance of 13.5 seconds when the imposed top lateral displacement reached 85 mm.

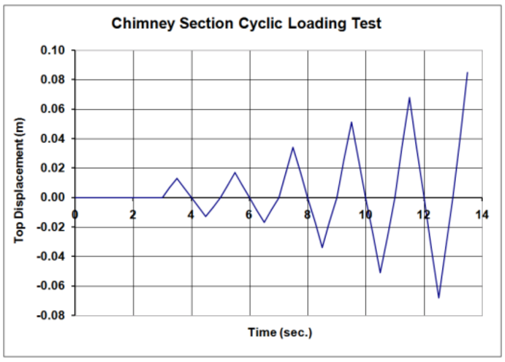

Figure 7. Dynamic loading function used for the imposed displacement-controlled cycles

Figure 8 illustrates the LS-Dyna finite element mesh used in this study. The concrete shell of the test chimney was modeled with two layers of hexahedral elements. Figure 9 shows the finite element mesh around the two opening regions.

The finite element mesh consisted of approximately 10,000 hexahedral elements representing the concrete shell, and 3,000 line elements representing the reinforcements. The cyclic loading was applied to the top nodes of the chimney given in Figure 8. The line elements representing the reinforcements were placed at the middle of the shell thickness.

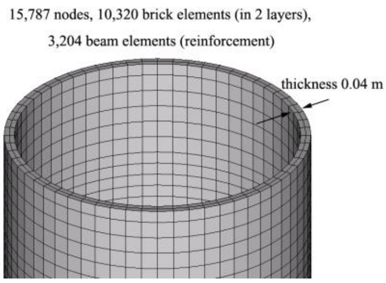

Figure 8. Finite element mesh at the top of the chimney section

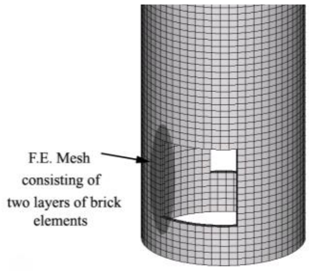

Figure 9. Finite element mesh around the opening regions

The concrete shell of the chimney had an unconfined compressive strength of 40 MPa. In order to simulate a realistic gravity loading on the chimney section, an axial force of 226 KN was applied on the chimney before it was subjected to the cyclic loading at the top section. The 30 counts of 5.8 mm diameter longitudinal reinforcements were reported to have a yield stress of 530 MPa, a stress of 580 MPa at 5% strain, and an ultimate stress of 600 MPa at 8% strain in the experimental study [4]. The longitudinal reinforcement ratio was 0.53%.

Additional reinforcements were provided around the openings in terms of 3 counts of 5.8 mm diameter rebars on each side of the opening at a distance of 0.10 m from the edge. The hoop reinforcement of the chimney consisted of 4.8 mm diameter rebars placed in with a center-to-center spacing of 80 mm. The hoop reinforcement ratio was 0.45%.

3. NONLINEAR MATERIAL MODELS USED IN THE STUDY

Figure 10 gives the stress-strain relationship for the rebar material used in the analysis. The material model exhibits a bi-linear response with a yield stress of 530 MPa and an ultimate stress of 600 MPa at 8% strain. The bi-linear model was chosen to be representative of the reinforcement used in the test because the small diameter rebars were not expected to exhibit a large yield plateau.

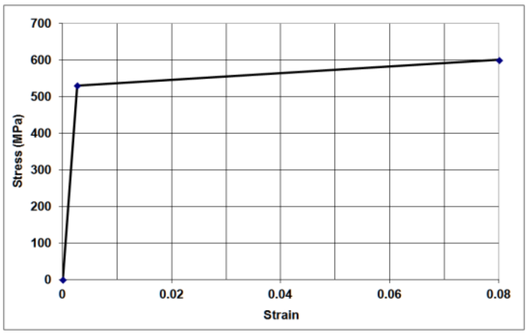

Figure 10. Bi-linear material model used for reinforcements

LS-Dyna offers various material models for analyzing concrete structures. The Winfrith concrete model was chosen for the analysis of the chimney due to its ability to represent the triaxial failure state of concrete [7-10]. This model was based on the yield criterion originally developed by Ottosen [11,12] and its mathematical form is given in Eq. 2. The model utilizes the first invariant of the stress tensor and the second invariant of the deviatoric stress tensor, given in Equations 3 and 4, respectively.

$$a \cdot \frac{J_2}{(f_c^{'})^2} + \lambda(k_1, k_2) \cdot \frac{\sqrt{J_2}}{f_c^{'}} + b \cdot \frac{I_1}{f_c^{'}} = 1 \qquad (2)$$

a= First model parameter,
b= Second model parameter,
$f_c^{'}$= Unconfined compressive strength,
k_1= Third model parameter,
k_2= Fourth model parameter.

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3 \qquad (3)$$

σ_1= First principal stress,
σ_2= Second principal stress,
σ_3= Third principal stress,
I_1= First invariant of the stress tensor.

$$J_2 = \frac{1}{6}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] \qquad (4)$$

J_2= Second invariant of the deviatoric stress tensor.

In Eq. 2, *a* and *b* represent constants determined from experiments, λ is a parameter that varies depending on the axial stress state. Figure 11 shows the Ottosen failure surface constructed for visualization purposes by the author, using the principal stresses as the coordinate axes.

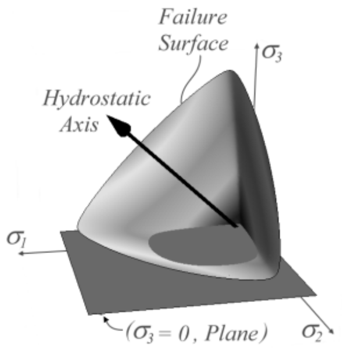

Figure 11. Ottosen failure surface visualization in the principal stress space

The Winfrith model can also incorporate crack formation in concrete based on a smeared-crack approach [9,10]. The cracks are assumed to be smeared out in a continuous fashion along planes perpendicular to the direction of principal tensile stresses.

Figure 12 shows the single hexahedral element model used in the calibration study of the Winfrith material in LS-Dyna. The bottom nodes of the element had hinge supports and the vertical loads were applied at the upper nodes. The unconfined compressive and the tensile strengths of the model were 20 MPa and 2 MPa, respectively. The numerical values used for the model parameters *a*, *b*, k_1 and k_2 were 1.276, 3.196, 11.74, 0.9801, respectively.

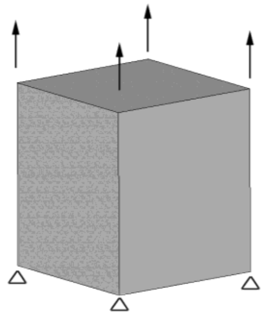

Figure 12. Boundary conditions and loads of the single element calibration study

Figure 13 shows the crack formation normal to the principal tensile stress obtained in the calibration study. Plots of element axial stresses are shown in Figure 14. The response under compressive loading is shown in Figure 14(a). When the element reached the compressive strength of 20 MPa, the axial stress stayed constant while plastic flow continued. The Winfrith model does not take the decay in compressive stresses after reaching the unconfined compressive strength.

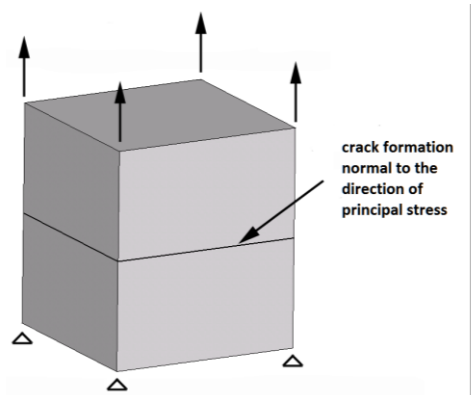

Figure 13. Horizontal crack formation in the single element calibration analysis

Figure 14(b) gives the response of the element under tensile loading. When the tensile strength of 2 MPa was reached, the element stress deteriorated. The element failed under tensile stresses and a crack normal to the principal stress direction formed.

Figure 14(c) illustrates the response of the brick element under cyclic loading. The first cycle consisted of compressive loading, which was followed by tensile force application. The compressive strength was maintained at 20 MPa during the compressive loading. The tensile phase reached a peak stress level of 2 MPa, the crack shown in Figure 13 occurred, followed by a post-strength decay. After attaining the tensile failure state, the loading was changed to compression and the tensile crack was closed. This condition allowed the element to regain its compressive strength.

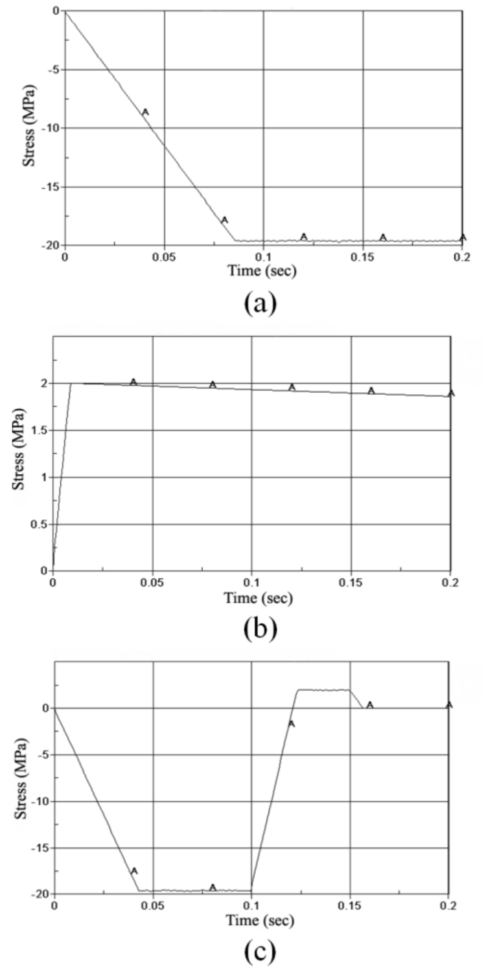

Figure 14. Single element calibration results for (a) unconfined compression, (b) unconfined tension, and (c) unconfined compression followed by tension

4. RESULTS OF THE FINITE ELEMENT STUDY

In the finite element study, the unconfined compressive and tensile strengths of concrete were input as 40 MPa and 4 MPa, respectively. The numerical values used for the concrete material model parameters *a*, *b*, k_1 and k_2 were 1.276, 3.196, 11.74, 0.9801, respectively. The steel material model is illustrated in Fig. 10.

The base moment versus tip displacement response of the chimney is given in Fig. 15. The finite element results obtained from the LS-Dyna analysis were compared with the experimental results reported by Wilson [4]. The analysis captured the failure envelope of the test results but showed a stiffer response in general.

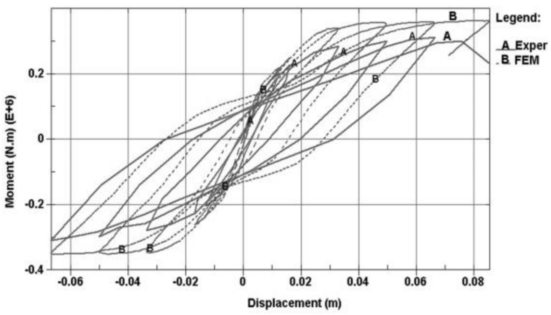

Figure 15. Base moment versus tip displacement comparison for the experimental and numerical studies

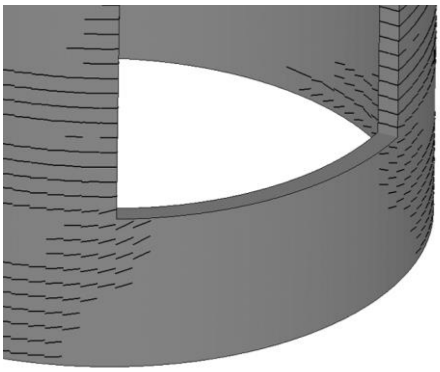

Figure 16. Horizontal crack formation and high strain localizations obtained in the finite element study

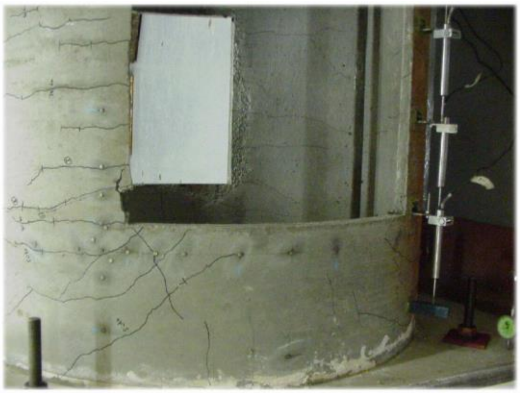

Figure 17. Crack formations around the opening regions observed during the test [3]

A close-up view around the two openings with the horizontal crack formations of the finite element study is given in Figure 16. The cracks observed in the experiment are shown in Figure 17 [3]. The horizontal cracks on the sides of the opening were in agreement with the crack formation pattern obtained in the numerical study.

5. SUMMARY AND CONCLUSIONS

A previous study at the University of Melbourne was conducted to investigate the experimental cyclic behavior of a reinforced concrete chimney section. The purpose of experimental study was to evaluate the seismic performance of chimney structures with large openings. In the current numerical study, a finite element model was constructed in order to match the results of the previous experimental study. The commercial structural analysis code LS-Dyna was used in the numerical study.

A bi-linear stress-strain model was used to model the behavior of reinforcement. The Winfrith concrete material of the LS-Dyna code was used for the concrete shell.

The displacement-controlled cyclic loading of the experiment was simulated in the LS-Dyna code by using an explicit time marching scheme. This approach made it possible to simulate complex material nonlinearity without the need to use an iterative approach. The longitudinal rebars and the additional opening reinforcements were explicitly modeled in the finite element analysis.

The overall response of the chimney in terms of the base moment versus tip displacement was captured by the finite element results. The numerical response was stiffer compared to the experimental results. The crack formations obtained in the finite element results showed good agreement with the cracks observed in the experimental study.

With the validation of the numerical model, further investigations of the chimney section for various cyclic loading orientations were made possible.

6. ACKNOWLEDGMENTS

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7. REFERENCES

1. Huang, W., Gould, P.L., Martinez, R., Johnson, G.S., 2004. Non-linear Analysis of a Collapsed Reinforced Concrete Chimney. Earthquake Engineering & Structural Dynamics, 33(4), 485-498.

2. Kilic, S.A., Sozen, M.A., 2003. Evaluation of Effect of August 17, 1999, Marmara Earthquake on Two Tall Reinforced Concrete Chimneys. ACI Structural Journal, 100(3), 357-364.

3. Wilson, J.L., 2003. Experimental Study to Investigate the Cyclic Behaviour of Reinforced Concrete Chimney Sections with Openings – Test #5. Research Report, Dept. of Civil & Environmental Engineering, University of Melbourne, Australia.

4. Wilson, J.L., 2009. The Cyclic Behaviour of Reinforced Concrete Sections with and without Openings. Advances in Structural Engineering, 12(3), 411-420.

5. Hallquist, J.O., 2006. LS-Dyna Theoretical Manual. Livermore Software Technology Corporation, Livermore, California, USA.

6. Bathe, K. J., 1996. Finite Element Procedures. Prentice Hall.

7. Broadhouse, B.J., Neilson, A.J., 1987. Modelling Reinforced Concrete Structures in DYNA3D. Proceedings of the DYNA3D User Group Conference, London, UK.

8. Broadhouse, B. J., 1992. DYNA3D Analysis of Cone Crack formation due to Heavy Dropped Loads on Reinforced Concrete Floors. Proceedings of the Structures under Shock and Impact Conference, WIT Press, Dorset, UK.

9. Broadhouse, B.J., Attwood, G.J., 1993. Finite Element Analysis of the Impact Response of Reinforced Concrete Structures Using DYNA3D. Proceedings of the Structural Mechanics in Reactor Technology Conference XII, Stuttgart, Germany.

10. Broadhouse, B.J., 1995. The Winfrith Concrete Model in LS-DYNA3D. Report No. SPD/D(95)363, Atomic Energy Authority, Winfrith Technology Centre, Dorset, UK.

11. Ottosen, N.S., 1977. A Failure Criterion for Concrete. Journal of the Engineering Mechanics Division, American Society of Civil Engineers (ASCE), 103(em4), 527-535.

12. Ottosen, N.S., 1979. Constitutive Model for Short-time Loading of Concrete. Journal of the Engineering Mechanics Division, American Society of Civil Engineers (ASCE), 105(em1), 127-141.