5. Also, there is a need for the development of a rational performance based fire engineering approach for the design of RC structures. For facilitating such an approach in fire safety design, guidelines on fire scenarios, high temperature material properties, loading configurations and failure criteria should be laid out.

ACKNOWLEDGMENT

The research, presented in this paper, is primarily supported by the Michigan State University, through the National Science Foundation CMMI program, grant number CMS 0601178.

REFERENCES

1. ACI/TMS Committee 216, "Code requirements for determining fire resistance of concrete and masonry construction assemblies (ACI 216.1-07/TMS-216-07)," American Concrete Institute, Farmington Hills, MI, 2007, 28 pp.
2. Phan, L.T., "Fire performance of high strength concrete: A report state of the art", National Institute of Standards and Technology Internal Report No. 5934, Gaithersburg, Maryland, USA, 1996.
3. Kodur, V.K.R. and McGrath, R., "Fire endurance of high strength concrete columns", *Fire Technology-Special Issue*, V. 39, No. 1, 2003, pp. 73–87.
4. Lie, T.T. and Woolerton, J.L., "Fire resistance of reinforced concrete columns – Test results", National Research Council of Canada, Institute for research in Construction, Internal Report No 569, Ottawa, Canada, 1988.
5. Aldea, C.M., Franssen, J.M. and Dotrppe, J.C., "Fire test on normal and high strength reinforced concrete columns", National Institute of Science and Technology – Special Publication, No. 919, Gaithersburg, Maryland, USA, 1997.
6. Ali, F.A., O'Connor, D. and Abu-Tair, A., "Explosive spalling of high strength concrete columns in fire", *Magazine of Concrete Research*, V. 53, No. 3, 2001, pp. 197-204.
7. British Standards Institutions (BSI), "Fire tests on building materials and structures. Method for determination of the fire resistance of elements of construction (general principles)", BS 476-20, UK, 1987.
8. Franssen, J.M. and Dotreppe, J.C., "Fire tests and calculation methods for circular concrete columns", *Fire Technology*, V. 39, 2003, pp. 89–97.

9. Kodur, V.K.R., “Fire resistance design guidelines for high strength concrete columns”, National Research Council, Canada, Internal Report No. 46116, 2003, pp. 1-11.

10. Kodur, V.K.R., Cheng, F.P. and Wang, T.C., “Effect of Strength and Fiber Reinforcement on the Fire Resistance of High Strength Concrete Columns,” *ASCE Journal of Structural Engineering*, 2003, Vol. 129, No. 2, pp. 253–259.

11. American Society for Testing and Materials (ASTM), “Standard methods of fire endurance tests of building construction and materials”, ASTM E119, Philadelphia, PA, USA, 2001.

12. Ali, F. A., Ali, N., Silcocka, G. and Abu-Tair, A., “Outcomes of a major research on fire resistance of concrete columns”, *Fire Safety Journal* V. 39, 2004, pp. 433–445.

13. Benmarce, A. and Guenfoud, M., “Experimental behavior of high strength concrete columns in fire”, *Magazine of Concrete Research*, V. 57, No. 5, 2005, pp. 283–287.

14. Lie, T.T. and Celikkol, B., “Method to calculate the fire resistance of circular reinforced concrete columns”, *ACI Materials Journal*, V. 88, No. 1, 1991, pp. 84-91.

15. Canadian Standards Association (CSA), “Code for the design of concrete structures for buildings”, CAN3-A23.3-M94, Rexdale, ON, Canada, 2004.

16. Lie, T.T., and Irwin, R.J., “Method to calculate the fire resistance of reinforced concrete columns with rectangular cross section”, *ACI Structural Journal*, V. 90, No.1, 1993, pp. 52-60.

17. EN 1992-1-2, Eurocode 2, “Design of concrete structures – Part 1-2, General rules – Structural Fire design, CEN, 2004.

18. Kodur, V.K.R., Wang, T.C. and Cheng, F.P., “Predicting the fire resistance behavior of high strength concrete columns”, *Cement and Concrete Composites*, V. 26, No. 2, 2004, pp. 141-153.

19. Tan, K.H. and Yao, Y., “Fire resistance of four-face heated reinforced concrete columns”, *Journal of Structural Engineering*, V. 129, No. 9, 2003, pp. 1220-1229.

20. Tan K.H. and Yao Y., “Fire resistance of reinforced concrete columns subjected to 1-, 2-, and 3-face heating”, *Journal of Structural Engineering*, V. 130, No. 11, 2004, pp. 1820-1828.

21. Bratina, S., Cas, B., Saje, M. and Planinc, I., “Numerical modeling of behavior of reinforced concrete columns in fire and comparison with Eurocode 2”, *International Journal of Solids and Structures*, V. 42, No. 21-22, 2005, pp. 5715-5733.

22. Holmberg, S. and Anderberg, Y., "Computer Simulations and Design Method for Fire Exposed Concrete Structures", Swedish Fire Research Board, Document No 92050-1, Lund, Sweden, 1993.

23. ACI Committee 318, "Building code requirements for structural concrete (ACI 318-05) and Commentary (ACI 318R-05)," American Concrete Institute, Farmington Hills, MI, 2005, 430 pp.

24. AS-3600, "Concrete Structures", Australia, Committee BD-002, 2001.

25. Kodur, V.K.R. and McGrath, R., ''Performance of High Strength Concrete Columns Under Severe Fire Conditions,'' Proceedings Third International Conference on Concrete Under Severe Conditions, Vancouver, BC, Canada, 2001, pp. 254–268.

26. Kodur, V.K.R., Cheng, F.P. and Wang, T.C., ''Effect of Strength and Fiber Reinforcement on the Fire Resistance of High Strength Concrete Columns,'' *ASCE Journal of Structural Engineering*, 2003, Vol. 129, No. 2, pp. 253–259.

27. Kodur, V.R., ''Fiber-Reinforced Concrete for Enhancing the Structural Fire Resistance of Columns,'' *Fiber-Structural Applications of Fiber-Reinforced Concrete*, ACI SP-182, 1999, pp. 215–234.

28. Danielsen, Ulf., ''Marine Concrete Structures Exposed to Hydrocarbon Fires,'' Report, SINTEF – The Norwegian Fire Research Institute, 1997, pp. 56–76.

29. Bilodeau, A., Malhotra, V.M. and Hoff, G.C., ''Hydrocarbon Fire Resistance of High Strength Normal Weight and Light Weight Concrete Incorporating Polypropylene Fibres,'' International Symposium on High Performance and Reactive Powder Concrete, Sherbrooke, QC, 1998, pp. 271–296,

30. V.K.R. Kodur, L. Phan, "Critical factors governing the fire performance of high strength concrete systems," *Fire Safety Journal,* 42 (2007) 482–488

31. Ali, F.A., Nadjai, A., Glackin, P. and Silcock, G., ''Structural Performance of High Strength Concrete Columns in Fire,'' Proceedings of the Seventh International Association of Fire Safety Science Symposium, Worcester, MA, USA, 2002, pp. 1001–1012.

32. Hertz, K.D., ''Limits of Spalling of Fire-Exposed Concrete,'' *Fire Safety Journal*, 2003, Vol. 38, pp. 103–116.

33. Kodur, V.K.R., ''Spalling in HSC Exposed to Fire: Concerns, Causes, Critical parameters and Cures,'' Proceedings, ASCE Structures Congress, Philadelphia, PA, 2000.

34. Kodur V.K.R., McGrath R. Effect of silica fume and confinement on fire performance of high strength concrete columns. Can J Civ Eng 2006;33:93–102.

35. Kodur, V.K.R., ''Spalling in HSC Exposed to Fire: Concerns, Causes, Critical parameters and Cures,'' Proceedings, ASCE Structures Congress, Philadelphia, PA, 2000.

5

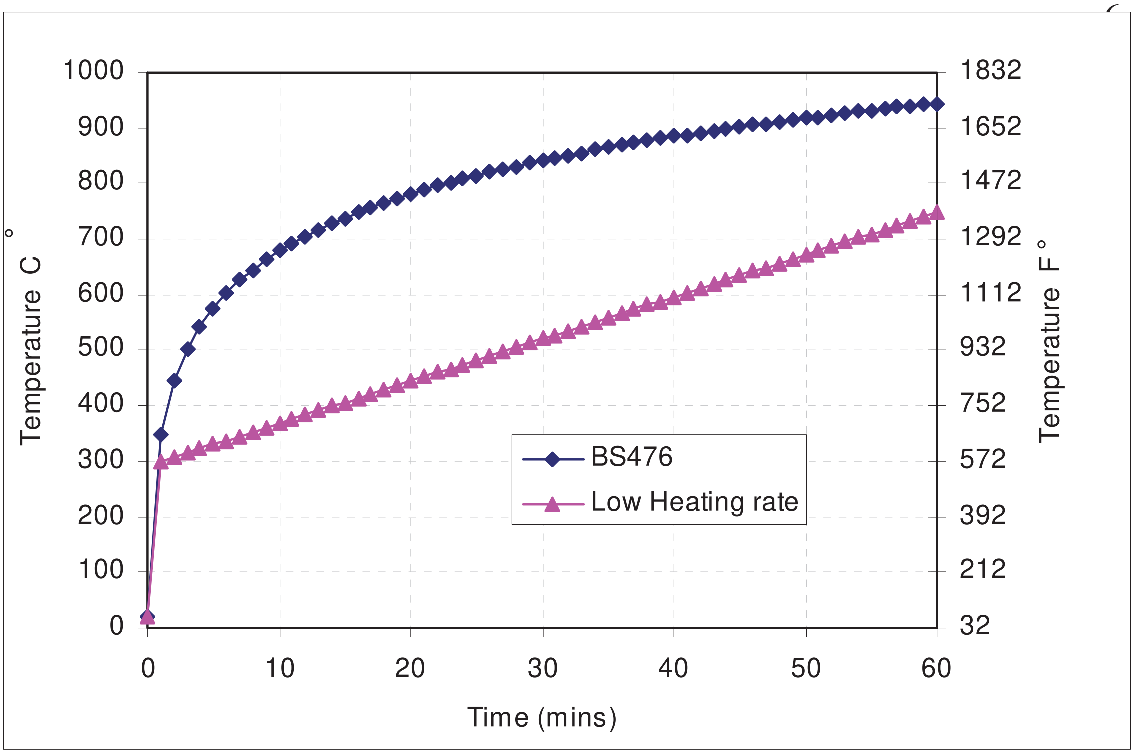

Figure 1 Heating rates used for fire tests on RC columns[6].

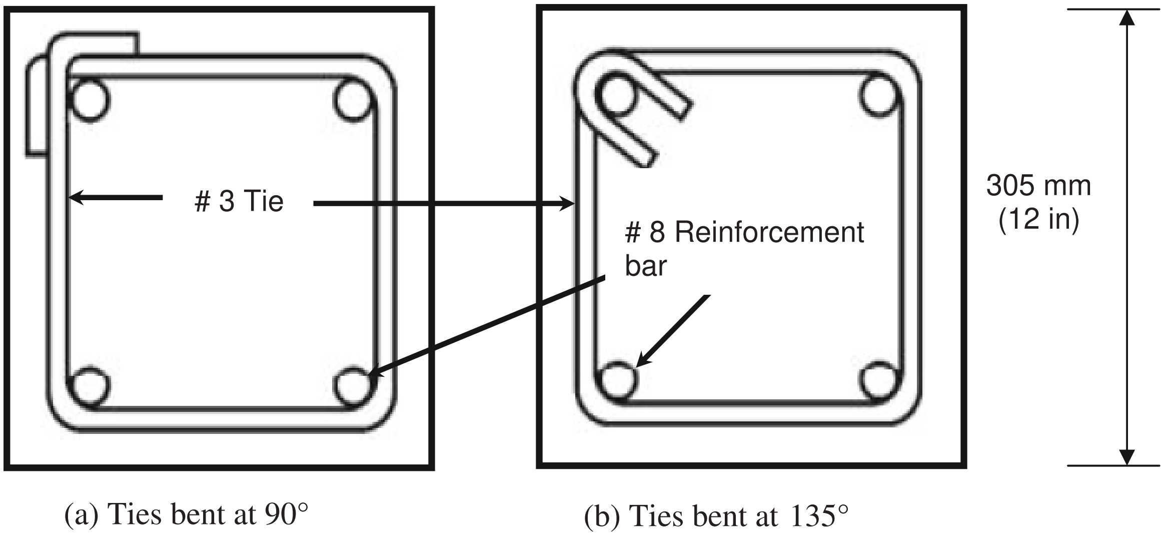

Figure 2 Typical layout of ties used in RC columns[9].

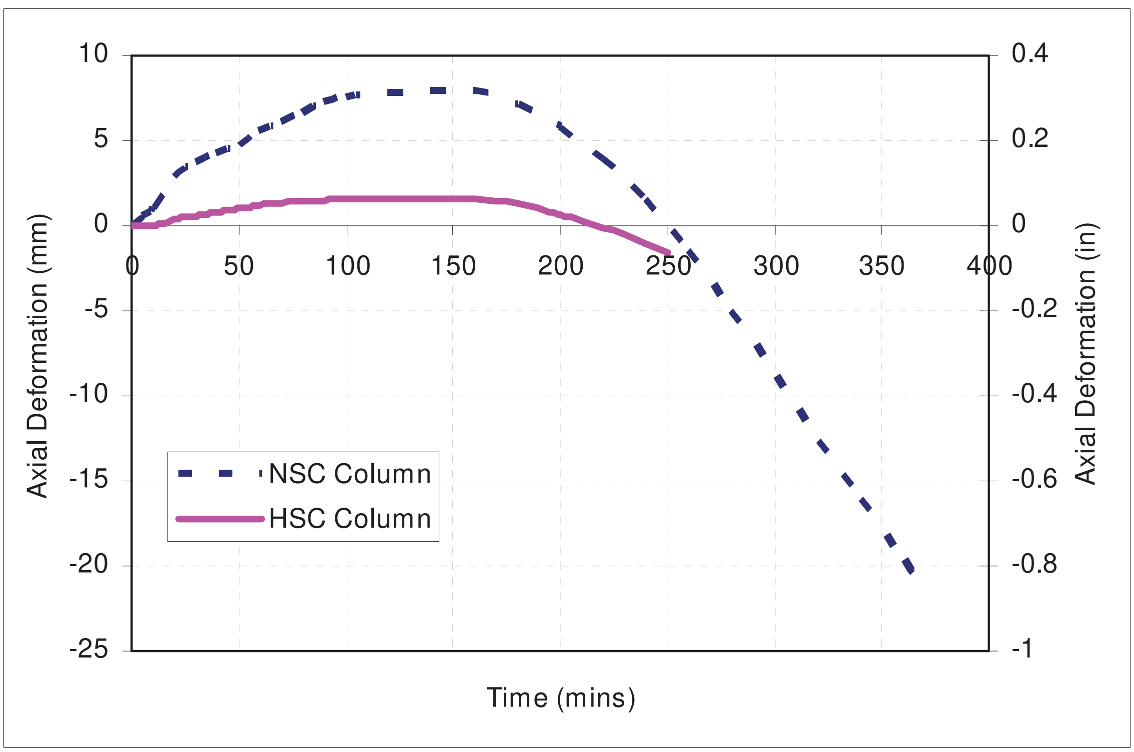

Figure 3 Axial deformation for the HSC and NSC columns[9].

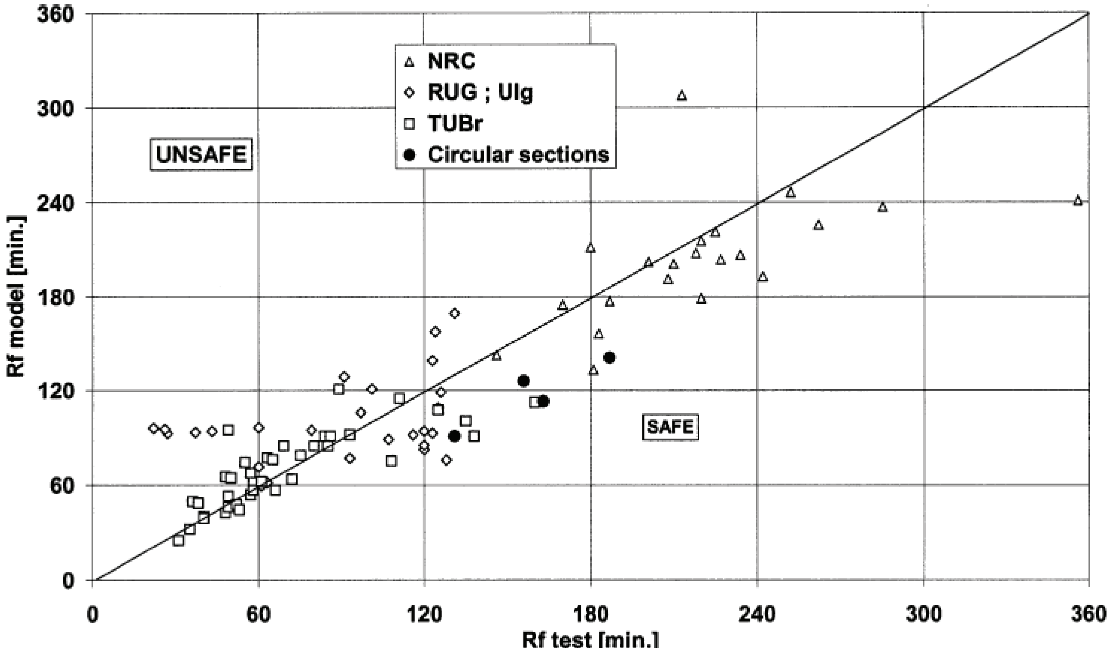

Figure 4 Comparison of fire resistance predictions from simplified equation and test data[8].

Comparisons of Fire Resistance of RC Beams from Different Codes of Practice

by M.B. Dwaikat and V.K.R Kodur

Synopsis: The fire resistance of reinforced concrete beams, computed as per three codes, namely, ACI 216.1, Eurocode 2, and AS 3600, is compared with that predicted from finite element analysis. A macroscopic finite element model, capable of tracing the behavior of restrained reinforced concrete beams from pre-fire stage to collapse, is used in the analysis. The model accounts for high temperature material properties, fire-induced strains (thermal, transient, and creep strains in addition to mechanical strain) and restraint effects as a result of fire exposure. Since restraint has a significant effect on fire resistance of reinforced concrete beams, the comparison is carried out for four cases of reinforced concrete beams with different boundary conditions. The first case represents a simply supported beam, while the other three cases represent axially restrained, rotationally restrained, and axially and rotationally restrained beams, respectively. Through the results of the case studies, it is shown that there is a large variation in the fire resistance predictions from the three codes, with Eurocode 2 being the most conservative and ACI 216.1 being the least conservative. It is also shown that the degree of axial restraint, rotational restraint, and type of failure criteria have significant influence on the fire resistance of reinforced concrete beams.

Keywords: design codes; fire resistance; fire resistance standards; high temperature; reinforced concrete beams; restraint effect

M.B. Dwaikat is a Ph.D. Candidate in the Department of Civil and Environmental Engineering. He received his MSc degree from University of Manchester (UMIST) in 2004. His research interests include fire resistance of reinforced concrete structures.

ACI member Dr. **Venkatesh Kodur** is a Professor in the department of Civil & Environmental Engineering at Michigan State University, East Lansing, MI 48824-1126. He is a Fellow of ASCE, Chairman of ACI-TMS Committee 216, and an Associate Editor of Journal of Structural Engineering. Dr. Kodur's research has focused on the evaluation of fire resistance of structural systems; characterization of the materials under high temperature (constitutive modeling); performance based fire safety design of structures; and non-linear design and analysis of structural systems.

INTRODUCTION

Reinforced concrete (RC) structural systems are quite frequently used in high-rise buildings and other built infrastructure due to a number of advantages they provide over other materials. When used in buildings, the provision of appropriate fire safety measures for structural members is an important aspect of design since fire represents one of the most severe environmental conditions to which structures may be subjected in their life time. The fire resistance of RC members is generally established using prescriptive approaches which are based on either standard fire resistance tests or empirical calculation methods.

The current provisions for fire resistance evaluation in codes of practice are mostly prescriptive. While the Eurocode specifications[1] provide some options for performance based fire resistance design, the specifications in American standards are highly prescriptive[2]. In addition, there are major variations in the fire resistance specifications among different codes of practice. As an illustration, a simply supported beam with width of 300 mm (11.8 in) and concrete cover thickness of 40 mm (1.6 in) has a fire resistance of about 210 minutes based on ACI 216.1 Specifications[2]. However, Eurocode 2[1] provisions predict a fire resistance of 120 minutes for this beam. Furthermore, the degree of axial restraint for reinforced concrete beams is not clearly addressed in codes for fire safety design.

RC beams can develop significant restraint forces under fire exposure. The degree of restraint is dependent on the support conditions and will determine the fire behavior and resistance of RC beams. The effect of axial restraint on the fire resistance of RC beams depends on the vertical location (along the sectional height) of the restraint force.

Generally, the axial restraint force in an RC beam is expected to improve the fire resistance of the RC beam through the arch action associated with axial restraint, which increases the strength and the stiffness of the beam under fire exposure[3]. However, axial restraint forces may lead to spalling of concrete or buckling of the beam (particularly for slender beams) which in turn might reduce the fire resistance of RC beams. Rotational restraint, under fire conditions, is also expected to improve the fire response of an RC beam through the moment redistribution between span (positive moment) and support (negative moment) sections within the length of the beam. Thus, it is essential to account for the fire induced restraint effects for evaluating realistic response of RC beams. At present, design codes, such as ACI 216.1[2], do not fully account for the fire induced restraint effects in RC beams.

There have been only limited studies on evaluating the fire performance of RC beams. Further, much of the current knowledge on the fire behavior of RC beams is based on standard fire resistance tests under standard fire exposure. Also, the failure is often based on thermal criterion (critical temperature in reinforcing bars) alone, without any due consideration to strength or deflection criterion. There have been limited research studies on evaluating the fire performance of RC beams under realistic (design) fire scenarios. Thus, there is no reliable experimental data, mathematical models or design specifications for predicting the fire resistance of RC beams under design fire scenarios. Additionally, the current approach of determining fire resistance of RC beams, which is generally specified by codes of practice, does not account for a number of factors such as realistic load levels, degree of restraint and actual failure criteria.

This paper presents a comparison of the fire resistance predictions of RC beams from three codes of practice; namely, ACI 216.1[2], Eurocode 2[1], and AS 3600[4], with those obtained from the analysis using a macroscopic finite element model[3]. The comparison is illustrated for four RC beams with different support conditions. The first beam is simply supported, while the remaining three beams are axially restrained, rotationally restrained, and both axially and rotationally restrained, respectively.

CODES OF PRACTICE

In the USA, concrete structures are to be designed in accordance with the American Concrete Institute (ACI-318) standard[5]. While ACI 318 does not contain any fire provisions, it refers to ACI 216.1 standard which gives specifications for fire resistance design of concrete and masonry structures. This standard provides the minimum width and concrete cover thickness required for achieving the required fire resistance rating for RC beams. These requirements differ for restrained and unrestrained support conditions of RC beams as can be seen in Table 1.