Solutions for Enhancing the Fire Endurance of HSS Columns Filled with High-Strength Concrete

V.K.R. KODUR

This paper is published with permission from the National Research Council of Canada.

Steel hollow structural section (HSS) columns are very efficient structurally in carrying compression loads and moments and are widely used in the construction of framed structures in office and industrial buildings. Often these sections are filled with concrete to enhance the load-bearing capacity. The two components of the composite column complement each other ideally, in that the steel casing confines the concrete laterally, allowing it to develop its optimum compressive strength, while the concrete, in turn, enhances resistance to elastic local buckling of the steel wall.

Another advantage of concrete filling is that it also increases fire resistance of the column without the need for external fire protection for the steel. This increases usable space in the building. Properly designed concrete-filled columns can lead economically to the realization of architectural and structural design with visible steel without any restrictions on fire safety (Kodur and Lie, 1995; Klingsch and Wuerker, 1985).

In recent years, high-strength concrete (HSC) has become an attractive alternative to traditional normal-strength concrete (NSC) since it further increases the load-carrying capacity of HSS columns (Prion and Baraka, 1994; Kodur, 1998). As well, the high stiffness of HSC prevents elastic local buckling in the steel wall while the confinement within the steel HSS enhances the ductility, which sometimes is a major concern for HSC. These advantages have led to the increased use of HSC-filled HSS columns, and some of the recent buildings on the West Coast of the United States using this type of construction are given in Table 1 (Ghosh, 1997).

The benefits from the use of HSC filling can be maximized if the external fire protection is eliminated. The enhancement of fire resistance of HSS columns, leading to the use of unprotected concrete-filled HSS columns, has been established for NSC filling [concrete strength below 55 MPa (8,000 psi)] by a number of studies (Kodur and Lie, 1995; Lie and Kodur, 1996a; Kodur, 1999). However, there is little information available in the literature on the fire performance of HSS columns filled with HSC [strength above 55 MPa (8,000 psi)]. Further, the behavior of HSC at elevated temperatures is significantly different from that of NSC (Phan, 1996; Kodur and Sultan, 1998).

To develop fire resistance information on high-strength concrete-filled HSS columns, experimental and numerical studies were carried out on these columns. In this paper, results of the fire resistance of HSS columns filled with HSC concrete are presented for three types of concrete filling. A comparison is made of the fire resistance of NSC- and HSC-filled HSS columns. Solutions are suggested for enhancing the fire resistance of HSC-filled HSS columns.

Table 1. HSC-Filled HSS Columns in Buildings

Building	No. of Stories	f'_c, MPa (psi)
Two Union Square (Seattle, WA)	62	97 (14,000)
Pacific First Center (Seattle, WA)	44	97 (14,000)
Gateway Tower (Seattle, WA)	63	76 (11,000)
600 California (Los Angeles, CA)	20	66 (9,600)

V.K.R. Kodur is senior research officer, Fire Research Program, Institute for Research in Construction, National Research Council of Canada, Ottawa, Canada.

BEHAVIOR OF CONCRETE-FILLED STEEL COLUMNS

The behavior of HSS columns filled with concrete, when subjected to fire, depends on the temperature range and the duration of the fire. This is illustrated by the axial deformation versus time plot in Figure 1 for a typical HSS column filled with NSC exposed to heat in a furnace, specially built for testing loaded columns under standard (ASTM E119) fire conditions (Kodur and Lie, 1995). During the early stages of fire exposure, the steel column carries most of the load. This is because the steel section expands more rapidly than the concrete core. At increased temperatures, the steel section yields because of decreasing strength and the column suddenly contracts, usually at 20 to 30 min. This contraction is often accompanied by local bulging of the steel section. At this stage, the concrete core takes over the load and carries a progressively increasing portion of the load with increasing temperature. Concrete, due to its lower thermal conductivity and higher heat capacity, loses strength more slowly than steel and provides fire resistance for the column at these later stages of the test.

The strength of the concrete also decreases with time and, ultimately, when the concrete core can no longer support the load, failure occurs either by buckling or by compression. The length of time the concrete (NSC) is capable of supporting the load can be quite significant, as seen from Figure 1. However, it has been shown that the fire performance behavior of HSC, under fire conditions, is different from NSC and this might have significant effect on the resulting fire resistance of HSC-filled HSS columns (Phan, 1996; Kodur, 1998). In this paper, the effects of concrete strength and the type of concrete filling on fire resistance are investigated using the test results for six HSS columns filled with various concrete types and strength.

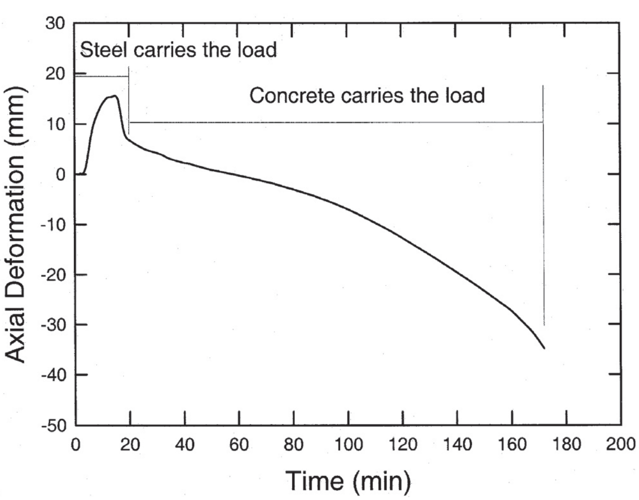

Fig. 1. Expansion of concrete-filled columns during exposure to fire.

EXPERIMENTAL STUDIES

Six concrete-filled steel columns, designated HSS1 to HSS6, were tested to failure by exposing the columns to the standard fire. The columns had circular and square cross sections and were filled with concrete of varying strength and type: HSS1 and HSS3 were filled with NSC, HSS2 with plain HSC, HSS4 and HSS5 with fiber-reinforced HSC (FC), while HSS6 was filled with bar-reinforced HSC (RC). No external fire protection was provided for the steel.

All columns were 3,810 mm (12.5 ft) long. Columns HSS1 and HSS2 had an outside diameter and thickness of 273.1 × 6.35 mm (10.75 × 0.25 in.), and the corresponding sectional dimensions for columns HSS3 and HSS4 were 219.1 × 4.78 mm (8.625 × 0.18 in.). The square columns HSS5 and HSS6 were 203.4 mm (8 in.) wide and 6.35 mm (0.25 in.) thick. The average 28-day cylinder strength of the NSC was 36 MPa (5,220 psi) and 43 MPa (6,240 psi), while the corresponding strength for HSC varied from 82 to 91 MPa (11,900 to 13,200 psi).

For the RC filling (column HSS6), the reinforcing bars were tied together to form a steel cage, which was placed inside the column. The longitudinal reinforcement consisted of four 16 mm (⅝ in.) rebars, while 6.4 mm (¼ in.) ties, provided at a spacing of 254 mm (10 in.), formed the lateral reinforcement. The cover to the main reinforcing bars was 23 mm (0.91 in.). For FC filling, steel fibers, 1.77% by mass, were mixed with the concrete. Thermocouples, with a thickness of 0.91 mm (0.036 in.), were installed at the mid-height of the column to measure temperatures at different locations in the cross section. Figure 2 shows elevation and cross-sectional details for typical HSS columns with PC, FC, and RC filling.

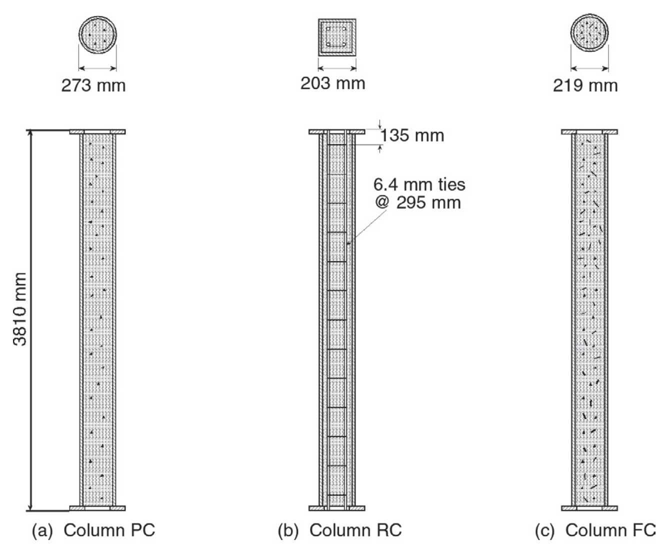

Fig. 2. Elevation and cross section of columns.

Table 2. Summary of Results for HSS Columns Filled with High Strength Concrete									
Column	HSS Dimensions (mm)	Reinforce-ment Type – %	Concrete Strength	Factored Resistance		Test Load	Load Intensity		Fire Resistance (minutes)
			f'_c 28 day (MPa)	C'_r 28 day (kN)	C_{rc} 28 day (kN)	C (kN)	C/C'_r 28 day	C/C_{rc} 28 day	
HSS1	273.1 × 6.35	–	35.9	947	2869	712	0.75	0.26	144
HSS2	273.1 × 6.35	–	90.5	2291	4023	1050	0.46	0.26	48
HSS3	219.1 × 4.78	–	43	699	1551	560	0.80	0.36	108
HSS4	219.1 × 4.78	*F – 1.75	90.1	1184	2032	600	0.51	0.30	174
HSS5	203.2 × 6.35	*F – 1.75	90.1	1236	2777	900	0.73	0.32	128
HSS6	203.2 × 6.35	*B – 2.2	81.7	1152	2693	1150	1.00	0.43	89

*F – steel fibers
*B – steel rebars

The tests were carried out by exposing the concrete-filled columns to heat in a furnace especially built for testing loaded columns. The test furnace was designed to produce conditions such as temperature, structural loads, and heat transfer, to which a member might be exposed during a fire. It consists of a steel framework with the furnace chamber inside it. The furnace facility includes a hydraulic loading system with a capacity of 1,000 tons.

The columns were subjected to constant concentric loads during testing. The applied load on the columns varied from about 46 to 100% of the factored compressive resistance of the concrete core (C_{rc}) or about 26 to 43% of the factored compressive resistance of the composite column (C_r'), calculated according to the specifications of Canadian Standard CSA/CAN3-S16.1-M89 (CSA, 1989). These load levels are in the same range as for AISC specifications. The load intensities were varied to gauge the effect of load on fire resistance. All the columns are of fixed-end conditions. The load was maintained constant throughout the test.

During the test, the column was exposed, under a load, to heating controlled in such a way that the average temperature in the furnace followed, as closely as possible, the ASTM E119-88 (ASTM, 1990) standard temperature-time curve. The columns were considered to have failed and the tests were terminated when the hydraulic jack, which has a maximum speed of 76 mm/min (3 in./min), could no longer maintain the load. The furnace, concrete, and steel temperatures, as well as the axial deformations and rotations, were recorded until failure of the column.

A summary of the column specifications together with results, as obtained from tests, is presented in Table 2. Full results of the fire tests on all columns are documented by Lie and Chabot (1992) and Kodur (1998).

RESULTS AND DISCUSSION

Results presented in Table 2 are used to discuss the performance of the HSC-filled HSS columns and to determine the factors influencing fire resistance. The effect of concrete strength on the behavior of HSS columns is illustrated by comparing the data from an NSC-filled column (HSS1) with an HSC-filled column (HSS2). The effect of steel fiber reinforcement in HSC mix on the fire resistance is illustrated by comparing results from columns HSS3 and HSS4, while the effect of bar reinforcement on fire performance is discussed with reference to columns HSS5 and HSS6. Although the load intensities for the columns are not identical, the results can be used to illustrate the comparative behavior of various types of HSC-filling.

Effect of Concrete Strength

The effect of concrete strength on the behavior of concrete-filled HSS columns can be assessed by comparing the results from columns HSS1 and HSS2 shown in Table 2. Except for concrete strength, these columns had similar characteristics and were subjected to load intensity (C/C_{rc}) of 0.26. Fire resistance of the HSC-filled steel column (HSS2) is 48 min, which is much less than that for the NSC-filled column, HSS1, which was 144 min. In comparison, the fire resistance of a similar unprotected and unfilled HSS column is about 20 min.

This degradation in performance of HSC-filled HSS columns could be explained by comparing the variation of temperature and deformations with time for NSC and HSC-filled HSS columns. The temperatures at external column surface and for depths of 33 and 98 mm (1.3 and 3.9 in.) in the concrete are plotted in Figure 3 for columns HSS1 and HSS2. For both columns, the temperatures inside the column (center) rise rapidly to about 150 °C (302 °F) and then the rate of increase of temperature decreases. This temperature behavior is due to the thermally induced migration of moisture toward the center of the column (Lie and Chabot, 1992). The influence of moisture migration is highest at the center of the column.

The failure of the NSC-filled HSS column (HSS1) occurred when the temperature at the center of the concrete core was approximately 550 °C (1,022 °F). The corresponding temperature at the center of the concrete core for the HSC-filled column (HSS2) was about 150 °C (302 °F). This

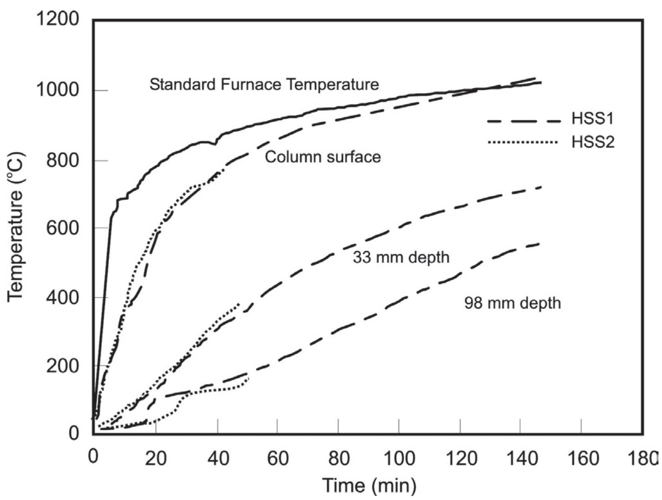

Fig. 3. Temperature at various depths for columns HSS1 and HSS2 as a function of exposure time.

variation in core temperature at the failure of the columns can be attributed to the differences in mechanical properties of the NSC and HSC (Kodur and Sultan, 1998; Phan, 1996). For both columns, the reduction in the compressive strength of the concrete with temperature, together with cracking in the concrete core, contributed to failure. However this reduction in strength with temperature starts only after about 350 to 400 °C (662 to 752 °F) for NSC. In the case of HSC, the reduction in compressive strength with temperature is significant even at temperatures around 200 °C (392 °F) and excessive cracking occurs in the concrete core. Hence, the HSC-filled HSS column has a lower fire resistance.

The variations in axial deformation with time for columns HSS1 and HSS2 are shown in Figure 4. As expected, both columns expand in the initial stages, with the expansion of the steel section, and then contract, leading to failure. The deformation results from several factors such as load, thermal expansion, water vapor pressure in concrete, and creep. While the effect of load, water vapor pressure, and thermal expansion is significant in the early stages, the effect of creep becomes pronounced in the later stages. The deformation behavior, in the later stages (after about 20 to 25 min), is mostly influenced by the strength of concrete inside the HSS section. For column HSS1, failure is by gradual contraction while for column HSS2, it is by sudden contraction. This can be attributed to the brittle nature of HSC.

Effect of Adding Fiber Reinforcement

The fire resistance of HSC, as well as its behavior under fire conditions, can be improved by adding steel fibers to the concrete mix. This can be seen by comparing the fire resistance of NSC-filled and steel fiber-reinforced HSC-filled HSS columns (Table 2). The fire resistance of steel fiber-

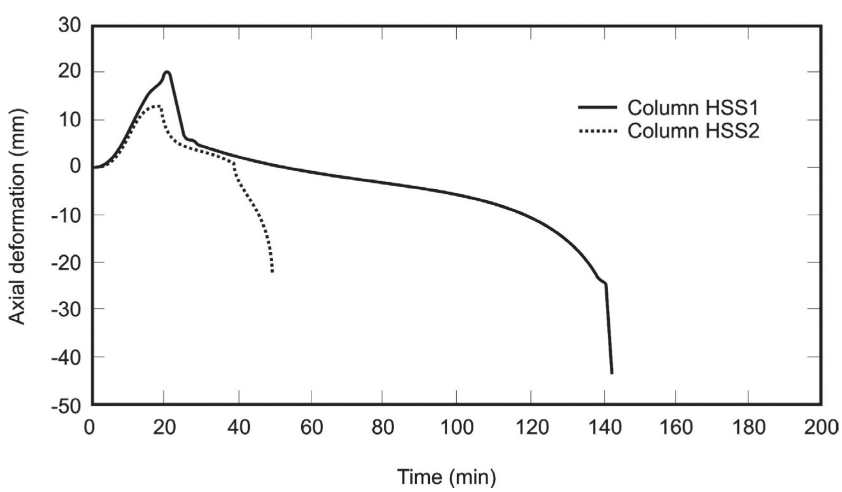

Fig. 4. Axial deformations of columns HSS1 and HSS2 as a function of exposure time.

reinforced HSC-filled HSS column (HSS4) is enhanced to 174 min as compared to 108 min for a similar HSS column filled with NSC (HSS3).

A comparison of time-temperature curves for the two HSS columns has shown that the temperatures follow similar trends in the concrete cores of both columns (Kodur, 1998). However, at the center of the column, the temperature in column HSS3 is lower than that for HSS4. Further, the failure of column HSS3 occurs when the temperature near the center reaches about 350 °C (662 °F), while the failure in column HSS4 does not occur until the temperature reaches about 600 °C (1,110 °F). It should be noted that at failure, the temperatures reached in the center of the concrete core in HSS3 [350 °C (662 °F)] was lower than that in column HSS1 [550 °C (1,020 °F)] due to the smaller size of the concrete core and higher applied loads.

Improved performance in the steel fiber-reinforced HSC-filled HSS column (HSS4) can further be seen in Figure 5, which shows the axial deformation as a function of time for columns HSS3 and HSS4. The deformation behavior of the fiber-reinforced HSC-filled column, HSS4, is similar, during the early stages of the test, to that of the NSC-filled steel column HSS3. At the later stages, column HSS4 performs better than column HSS3 since the presence of steel fibers enhanced the ductility of column HSS4. While the lower load intensity on column HSS4 contributed to an increased fire resistance to some extent, much of the contribution is from the presence of steel fibers in the HSC (Kodur, 1998; Kodur, 1997). This increased performance of HSC can be attributed to the superior mechanical properties of steel fiber-reinforced concrete and to the containment effect provided by the steel fibers to the concrete core (Lie and Kodur, 1996b; Kodur, 1998).

Effect of Adding Bar Reinforcement

Another alternative for enhancing the fire performance of HSC-filled HSS columns is to provide conventional rebars and ties inside the HSS column. The enhanced fire performance of these columns can be seen by comparing results for square columns HSS5 and HSS6. These two columns are of similar characteristics except for concrete type and load intensity. Column HSS5 was filled with fiber-reinforced HSC and column HSS6 was filled with bar-reinforced HSC; they were then subjected to a load intensity of 0.73 and 1, respectively. The higher load was applied in column HSS6 to determine the feasibility of obtaining practical fire resistance (1 to 2 hr) even under full service loads (equivalent to the strength of concrete core) with bar-reinforced HSC filling.

The fire resistance of the fiber-reinforced HSC-filled HSS column (HSS5) is 128 min while that for a bar-reinforced HSC-filled HSS column (HSS6) is 89 min. The lower fire resistance in column HSS6, as compared to HSS5, can be attributed to higher load intensity on this column. This illustrates that fire resistance of 1 hr or more can be obtained, even under loads equivalent to the strength of the concrete core, for HSC-filled steel columns through the addition of bar reinforcement. A lower load intensity (0.73 or less) would have resulted in a higher or at least similar fire resistance as that for column HSS5. Further, the results show that fire resistance as high as 2 hr can be obtained even for square HSS columns filled with fiber-reinforced HSC. It should also be noted that generally, square concrete-filled HSS columns have lower fire resistance compared to circular concrete-filled HSS columns (Kodur, 1999).

The variation in axial deformation with time for the two columns is shown in Figure 6. As expected, both columns

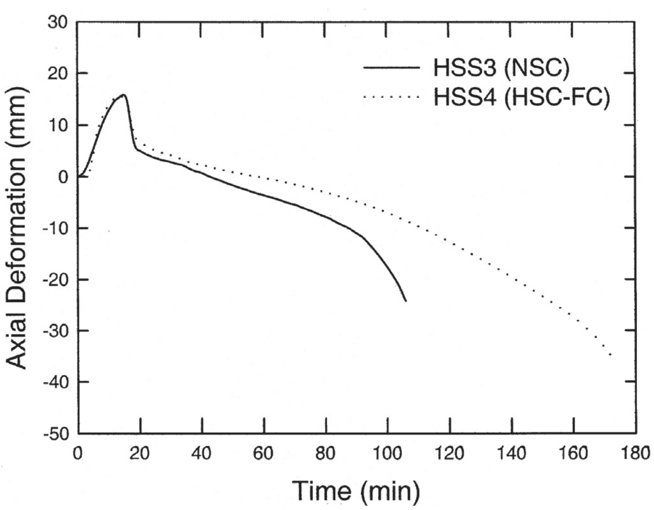

Fig. 5. Temperature at various depths for columns HSS3 and HSS4 as a function of exposure time.

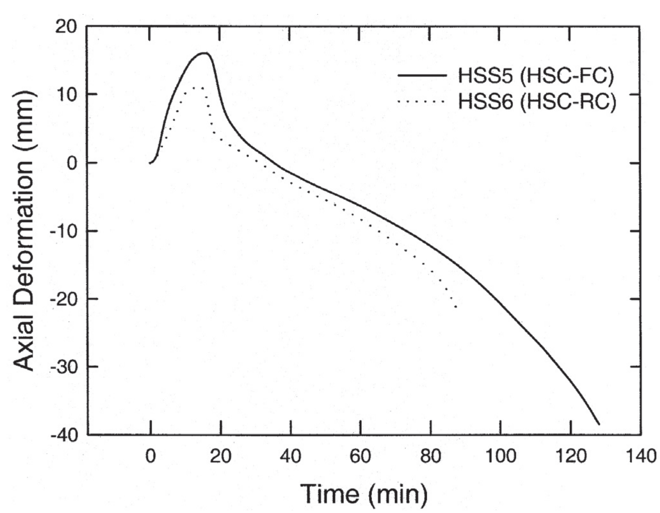

Fig. 6. Axial deformations of columns HSS5 and HSS6 as a function of exposure time.

expand in the initial stages and then contract, leading to failure. The deformation behavior of fiber-reinforced HSC-filled steel columns is similar, during the later stages of the test, to that of the bar-reinforced HSC-filled steel column. The higher deformations in column HSS5, as compared to column HSS6, are partly due to lower load intensity and higher thermal expansion of fiber-reinforced concrete. The deformation in column HSS6, prior to failure, is much smaller than the deformation in columns HSS5. Both columns failed in compression mode by gradual contraction. In the bar-reinforced concrete-filled HSS column, the presence of rebars not only decreases the propagation of cracks and sudden loss of strength but also contributes to the load-carrying capacity of the concrete core (Kodur and Lie, 1995).

DESIGN IMPLICATIONS

Concrete filling offers a practical solution for providing fire protection to HSS columns without any external protection. However, the strength and type of concrete used as filling has significant influence on the fire resistance. The fire resistance values of normal-strength, high-strength, and high-strength fiber-reinforced concrete-filled columns are compared in Figure 7. While fire resistance of up to 3 hr can be obtained for specific HSS columns filled with different types of NSC concrete filling, for HSC-filling, fire resistance up to 2 hr can be obtained. These fire resistance values are still within the practical range for most cases and under service loads. Based on the results presented in this paper and also other studies (Kodur, 1998; Kodur and Lie, 1995; Kodur, 1997; Kodur and MacKinnon, 2000), the following can be used as broad guidelines for fire resistance design of HSC-filled HSS columns having characteristics similar to those used in the studies.

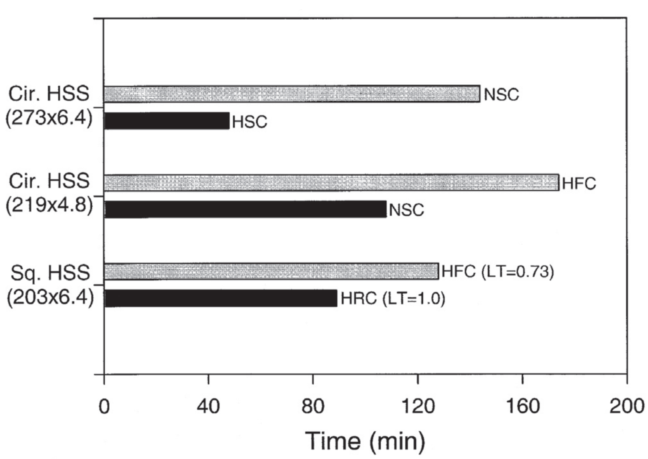

Fig. 7. Effect of concrete filling on the fire resistance of hollow steel columns.

- When HSS columns are filled with plain HSC filling, fire resistance of up to 45 min can be obtained. Since, in most practical situations, a minimum 1-hr fire resistance rating is required, plain HSC filling alone may not be sufficient to obtain the required fire resistance rating.

- The fire resistance of HSC-filled HSS columns can be enhanced by using steel fibers in the concrete mix. By filling HSS columns with steel fiber-reinforced HSC, fire resistance ratings of up to 2 hr can be obtained even at load intensity as high as 0.7. The addition of steel fibers, about 2% by mass, enhances the fire performance in these columns as well as the load-carrying capacity to a certain degree. The additional cost in the case of fiber-reinforced concrete-filled columns, over the cost of concrete, is the cost of the steel fibers and associated costs for mixing and placement of concrete. Since there is no additional fire protection costs for the steel, this can offer an economical solution for obtaining a required fire resistance rating where fire resistance governs the design.

- As an alternative to steel fiber reinforcement, conventional bar reinforcement can be used to enhance the fire resistance of HSC-filled HSS columns. Also, when the HSS columns are to be designed for high load levels (equivalent to the strength of concrete core), bar-reinforced HSC-filling should be used. Fire resistance up to 90 min can be obtained for these columns with load intensity of 1 and up to 2 hr when the load intensity is less than 0.75. Bar-reinforced HSC-filled HSS columns offer many of the advantages of columns filled with steel-fiber-reinforced HSC. They are, however, more expensive because of the labor involved in placing the reinforcing bars. They are also more difficult to work with in confined spaces with regard to achieving sufficient concrete coverage of the reinforcing bars.

CURRENT RESEARCH

The main objective of the experimental studies, such as those described above, is to generate fire resistance data for immediate use by the construction industry. These studies also provide information for the development of general methods of calculating fire resistance of concrete-filled steel columns.

Experimental and numerical studies have been completed for normal-strength concrete-filled steel columns, and design guidelines (Lie, 1994; Kodur and Lie, 1996; Kodur, 1998; Kodur and MacKinnon, 2000) have been developed for evaluating the fire resistance of these columns. At present, work is at an advanced stage in the development of material properties, namely, thermal, mechanical, and deformation properties for high-strength concrete and steel-fiber-reinforced high-strength concrete. These properties are required for modeling the behavior of HSC-filled HSS columns and to investigate the influence of various parameters on the behavior of high-strength concrete-filled HSS columns. Also, further experimental studies on HSC-filled HSS columns, as part of a major collaborative research project with the steel industry in North America and Korea (RIST), are being proposed.

Once the experiments and models are completed, they will be used to develop design equations for fire resistant design, which can be used in the normal course of structural design. A designer can arrive at a desired fire resistance value by varying different parameters. The use of computer programs can lead to an optimum design that is not only economical but is also based on rational design principles.

CONCLUSIONS

Based on the information presented, the following conclusions can be drawn:

1. Concrete filling offers an attractive alternative for producing fire resistance in HSS columns.

2. The behavior of HSC-filled steel columns is significantly different from that of NSC-filled HSS columns.

3. The fire resistance of HSC-filled HSS columns can be significantly improved by adding steel fiber reinforcement to concrete.

4. The fire resistance of HSC-filled HSS columns with high load levels can be enhanced through the use of conventional bar reinforcement.

CONVERSION FACTORS

1 in. = 25.4 mm

1 kip = 4.448 kN

1 ksi = 6.895 MPa

1 kip-ft = 1.356 kN-m

1 °F = (1 °C × 9/5) + 32

ACKNOWLEDGMENT

This paper was originally written on behalf of the National Research Council of Canada, thereby establishing a copyright belonging to the Government of Canada. A license was granted to AISC to print and publish this paper in the *Engineering Journal.*

REFERENCES

ASTM (1990), *Standard Methods of Fire Tests on Building Construction and Materials,* ASTM E119-88, Philadelphia, PA.

CSA (1989), *Limit State Design of Steel Structures,* CAN/CSA-S16.1-M89, Canadian Standard Association, Toronto, Ontario, Canada.

Ghosh, S.K. (1997), "High Strength Concrete in Regions of High Seismicity," *Proceedings*, ASCE Structures Congress, Vol. 2, Portland, Oregon, pp. 1001–1005.

Klingsch, W. and Wuerker, K. (1985), "New Developments in Fire Resistance of Hollow Section Structures," *Symposium on Hollow Structural Sections in Building Construction*, ASCE, Chicago, IL.

Kodur, V.K.R. (1998), "Performance of High Strength Concrete-filled Steel Columns Exposed to Fire," *Canadian Journal of Civil Engineering*, Vol. 25, No. 6, pp. 975–981.

Kodur, V.K.R. (1999), "Performance Based Fire Resistance Design of Concrete-rilled Steel Columns," *Journal of Constructional Steel Research Institute*, Vol. 51, pp. 21–36.

Kodur, V.K.R. (1997), "Design Equations for Evaluating Fire Resistance of SFRC-filled Steel Columns," ASCE, *Journal of Structural Engineering*, Vol. 124, No. 6, pp. 671–678.

Kodur, V.K.R. and Lie, T.T. (1995), "Fire Performance of Concrete-filled Hollow Steel Columns," *Journal of Fire Protection Engineering*, Vol. 7, No. 3, pp. 89–98.

Kodur, V.R. and MacKinnon, D.H. (2000), "Fire Endurance of Concrete-Filled Hollow Structural Steel Columns," AISC, *Engineering Journal*, Vol. 37, No. 1, pp. 13–24.

Kodur, V.R. and Sultan, M.A. (1998), "Structural Behaviour of High Strength Concrete Columns Exposed to Fire," *Proceedings: International Symposium on High Performance and Reactive Powder Concrete*, Vol. 4, Sherbrooke, Quebec, Canada, pp. 217–232.

Lie, T.T. and Chabot, M. (1992), "Experimental Studies on the Fire Resistance of Hollow Steel Columns Filled with Plain Concrete," *IRC Internal Report No. 611*, National Research Council of Canada, Institute for Research in Construction, Ottawa, Ontario, Canada.

Lie, T.T. and Kodur, V.K.R. (1996a), "Fire Resistance of Steel Columns Filled with Bar-reinforced Concrete," ASCE, *Journal of Structural Engineering*, Vol. 121, No. 1, pp. 30–36.

Lie, T.T. and Kodur, V.K.R. (1996b), "Thermal and Mechanical Properties of Steel Fibre-reinforced Concrete at Elevated Temperatures," *Canadian Journal of Civil Engineering*, Vol. 23, No. 4, pp. 511–517.

Phan, L.T. (1996), *Fire Performance of High-strength Concrete: A Report of the State-of-the-Art*, National Institute of Standards and Technology, Gaithersburg, MD.

Prion, H.G.L. and Baraka, M. (1994), "Thin-Walled Tubes Filled with High Strength Concrete," *Canadian Journal of Civil Engineering*, Vol. 21, No. 1, pp. 207–218.