Design of Concrete-Filled Hollow Structural Steel Columns for Fire Endurance

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ABSTRACT

The benefits of steel hollow structural sections (HSS) from an aesthetic and structural point of view have long been recognized by architects and engineers in Canada, and more recently in the United States. However, when building codes require structural fire protection, the cost of providing such protection can be expensive for exposed members. Filling an HSS column with concrete not only improves the capacity of the member through composite action at ambient temperatures but also provides fire endurance periods of up to 3 hours depending on the load level, section size, concrete strength and reinforcing characteristics. Physical tests and parametric studies recently completed at the National Fire Laboratory in Ottawa have resulted in design equations which predict the load carrying capacity and fire endurance period of concentrically loaded HSS columns filled with plain concrete, bar-reinforced concrete and steel fiber-reinforced concrete. The design method is presented, case studies are used to illustrate potential applications, and practical suggestions are made regarding construction techniques.

INTRODUCTION

Steel hollow structural sections (HSS) were first used as structural framing components in Canada in the early 1970's and, more recently, have gained popularity in the United States. Engineers find them to be very efficient structurally in resisting compression loads and architects like them since they are more visually pleasing than other shapes when exposed. In addition to the high profile projects such as the roof structure of the SkyDome in Toronto and the United Airlines Terminal at the O'Hare International Airport in Chicago, HSS are widely used as columns in the construction of ordinary steel-framed one-story structures and are being considered more often in two- and three-story buildings now that connec-

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tions involving these profiles are better understood (Packer and Henderson, 1997 and AISC, 1997).

One of the major safety requirements in building design is the provision of appropriate fire protection to structural members. This requirement can be attributed to the possibility of an unsuppressed fire causing a structural collapse or spreading to the floor above, both of which endangers the safety of evacuating occupants and emergency responders. The integrity of the horizontal fire separation or load carrying structure leads to the requirement that the supporting columns have equivalent fire endurance. Building codes in Canada (National Research Council of Canada, 1995) and the United States (ICBO, 1997) establish the length of time that a fire separation must contain a fire and the structural elements must endure a fire, based on the building's occupancy, size and height.

HSS columns are often filled with concrete in order to achieve increased load-bearing capacity through steel-concrete composite action. Concrete filling also increases fire resistance. Through the utilization of a concrete core, external fire protection required for the steel column can be eliminated, thus increasing the usable space in the building. Further, properly designed concrete-filled HSS columns can lead, in an economic way, to the realization of architectural and structural design with visible steel without any restrictions on fire safety.

Recently, the National Fire Laboratory (NFL), Institute for Research in Construction, National Research Council of Canada, in partnership with the Canadian Steel Construction Council and the American Iron and Steel Institute, developed guidelines for the simplified design and construction of concrete-filled HSS columns. Both experimental and theoretical studies, using computer models, were carried out to investigate the influence of concrete filling on the fire resistance and load capacity of HSS columns.

NRC STUDIES

Fire Tests

Fifty-eight concrete-filled HSS columns were tested to failure by exposing the columns to fire. The columns were of circular and square cross sections and were filled with three types of concrete; namely, plain concrete (PC), bar-reinforced concrete (RC) and steel fiber-reinforced concrete (FC). No exter-

nal fire protection was provided for the steel. Figure 1 shows elevation and cross-sectional details of typical circular HSS columns, filled with three types of concrete, used in the experimental study.

The tests were carried out by exposing the concrete-filled HSS columns to heat in a furnace specially built for testing loaded columns. The test furnace was designed to produce conditions, such as temperature, structural loads, heat transfer, to which a member might be exposed during a fire (Lie, 1980).

Most of the HSS columns tested were subjected to a concentric load. Only three columns were tested for eccentric loads. The applied load on the columns varied from about 60 to 140 percent of the factored compressive resistance of the concrete core and about 10 to 45 percent of the factored compressive resistance of the composite column calculated according to the specifications of CSA S16.1-94 (CSA, 1994) for the structural steel and CSA-A23.3-94 (CSA, 1994a) for the concrete.

During the test, the column was exposed to heating controlled in such a way that the average temperature in the furnace followed, as closely as possible, the standard time-temperature curve of ULC S101-89 (ULC, 1989), which is the same curve used in ASTM E119-88 (ASTM, 1988).

Full results of the fire tests on HSS columns, filled with PC, RC and FC are given in Lie and Chabot (1992), Chabot and Lie (1992), and Kodur and Lie (1995). Results from the fire tests indicate that the fire resistance of PC-filled HSS columns is about one to two hours, as compared to about 15 to 20 minutes for unprotected HSS columns. For RC-filled columns and FC-filled columns, fire resistance as high as three hours was obtained.

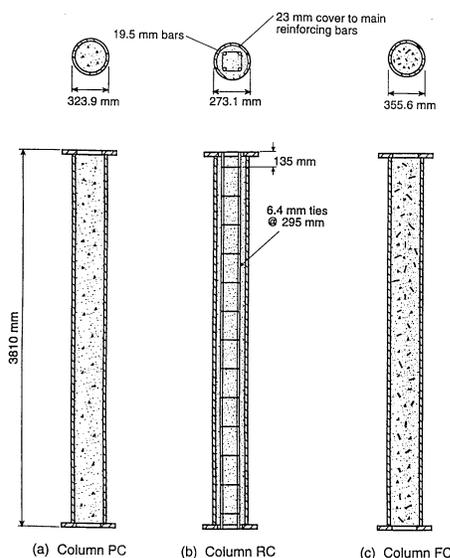The failure of the columns varied from compression failure of the concrete core to overall buckling depending on the size of the column and the type of filling. The majority of the PC-filled columns failed by overall buckling. Buckling was significant in columns with sectional dimensions less than 203 mm (8 in.). Generally, the failure of PC-filled columns was by sudden contraction, while RC-filled and FC-filled columns failed by gradual contraction.

The behavior of concrete-filled HSS columns under fire conditions is illustrated in Figure 2, which shows the variation of the axial deformation with time for the three types of concrete-filling (Kodur and Lie, 1995). These three columns had similar characteristics and were subjected to similar load levels. As expected, the columns expand in the initial stages and then contract leading to failure. The deformation in these columns results from several factors such as load, thermal expansion and creep. While the effect of load and thermal expansion is significant in the early stages, the effect of creep becomes pronounced in the later stages.

Numerical Models

Computer models were developed for predicting the behavior of PC, RC and FC-filled HSS columns in fire (Lie and Chabot, 1990; Lie and Kodur, 1996; Lie and Irwin, 1996; and Kodur and Lie, 1995b). The model incorporated realistic stress-stain relationships and the thermal properties for structural steel, concrete, and reinforcing steel at elevated temperatures. The validity of these computer programs has been established by comparing the predictions from the models to test data. The models can account for the important parameters that influence the fire performance of concrete-filled HSS columns.

The computer programs were used to carry out detailed numerical studies (Kodur and Lie, 1995a and 1995b) to compare the fire resistance of HSS columns with three types

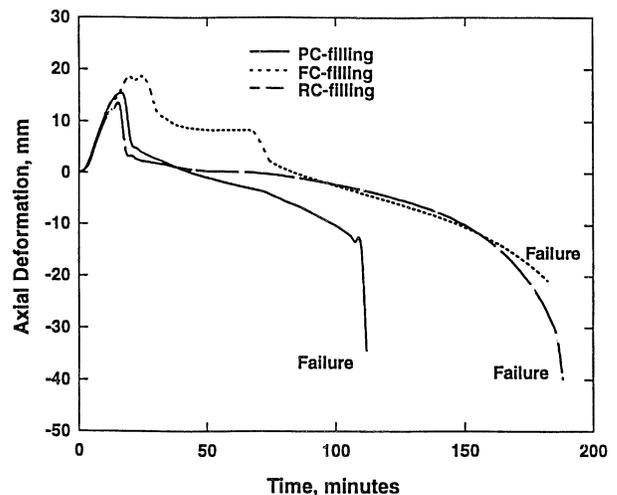Fig. 1. Elevation and cross section of typical concrete-filled HSS columns used in fire test.

Fig. 2. Comparison of axial deformations for concrete-filled HSS columns exposed to fire.

of concrete filling. The fire resistance of similar circular and square columns, as obtained from computer models, is compared for three types of concrete filling in Figure 3. The fire resistance of the PC-filled HSS columns is much less than the fire resistance of the RC and FC-filled HSS columns. The fire resistance of the FC-filled HSS columns is almost the same as that of the RC-filled HSS columns.

Although it is possible to use the computer models for fire resistance design, the calculation procedure is elaborate and requires considerable skill and effort. A method more suitable for general application and incorporation into codes, is the use of design formulas in line with conventional design procedures.

Parametric Studies

The computer programs described above were used to carry out detailed parametric studies to generate a large amount of data on the fire resistance of concrete-filled HSS columns. Detailed results of the parametric studies are presented by Lie and Kodur (Lie and Kodur, 1996 and Kodur, 1998).

The influence of various factors on the fire resistance of concrete-filled HSS columns was investigated through computer-simulated fire tests. Factors which influence the fire resistance and load capacity of PC-filled HSS columns were found to be:

- outside diameter (width) of steel section
- shape of the steel section
- load intensity and type
- wall thickness of steel section
- effective column length
- concrete strength, and
- type of concrete aggregate

The impact of these seven factors were found to be similar for RC and FC filling. However, the presence of steel fibers was found to have a significant influence on the fire resistance. For FC-filling, the content of steel fibers was held
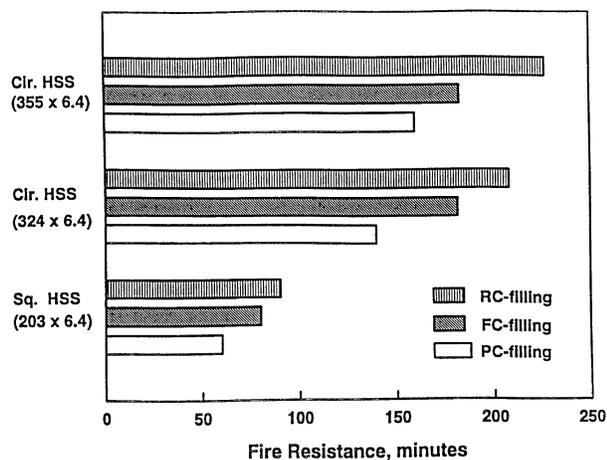

Fig. 3. Comparison of fire resistance for concrete-filled HSS columns.

constant at approximately 1.77 percent of the concrete mix by mass (Kodur and Lie, 1995 and 1995a).

For RC-filled HSS columns, two additional parameters have influence:

- percentage of bar-reinforcement, and
- concrete cover to bar-reinforcement

Simplified Equations for Fire Resistance

Based on the data from the parametric studies, expressions were developed for the calculation of the fire resistance of circular and square HSS columns filled with plain concrete, bar-reinforced concrete and steel fiber-reinforced concrete (Lie and Stringer, 1994; Lie and Kodur, 1996; and Kodur, 1998). Results from the parametric studies show that the most important parameters that determine the fire resistance of HSS columns filled with concrete are:

- outside diameter or the outside width of the column
- load on the column
- effective length of the column
- concrete strength
- type of aggregate
- type and percentage of reinforcement
- concrete cover thickness to reinforcement

Based on the relationships between the fire resistance and the above parameters, the following formula for the fire resistance of a concrete-filled HSS column subjected to axial loading, was established empirically (Lie and Stringer, 1994; Lie and Kodur, 1996; and Kodur, 1998):

$$R = f_1 \frac{(f_c' + 20)}{(KL - 1,000)} D^2 \sqrt{\frac{D}{C}} \qquad (1)$$

where:
R = fire resistance in minutes
f_c' = specified 28-day concrete strength in MPa
K = effective length factor
L = unsupported length of the column in mm
D = outside diameter or width of the column in mm
C = applied load in kN
f_1 = a constant to account for the cross-sectional shape, reinforcement, concrete cover thickness to bar-reinforcement and the type of aggregate used in the concrete mix

Validity limits were applied to Equation 1 including an upper limit for applied load, C, equal to the compressive resistance of the unreinforced concrete core, C'_r.

BEHAVIOR OF COMPOSITE COLUMNS

Results from the above studies can be used to describe the behavior of composite columns under fire conditions. At room temperature, the friction and mechanical bond at the steel concrete interface cause the steel and concrete to move

together. Since the strains are the same, both the steel section and the concrete core contribute to the total load carrying capacity of the composite column such that $C_{rc} = \tau\, C_r + \tau'\, C'_r$, where C_{rc} is the axial resistance of the composite column, C_r is the axial resistance of the steel section, C'_r is the axial resistance of the unreinforced concrete core and τ and τ' are the confinement amplification factors. Depending on the size of the steel section, concrete strength, reinforcing, etc., the core contributes from approximately 5 to 50 percent of the total capacity. For circular HSS columns, the strength of the concrete core is also significantly enhanced due to the confinement provided by the wall of the section. The benefit of this confinement effect is accounted for in CSA S16.1-94 (CSA, 1994) by multiplying the resistance of the concrete core, C'_r, by an amplifier, τ'.

As heat is applied, the steel will initially expand longitudinally (see Figure 2) more rapidly than the concrete and will therefore begin to resist a greater proportion of the applied load. At the same time, the yield strength of the steel and the elastic modulus decreases. Eventually, the steel will yield or buckle locally and the load in the steel begins to shift into the concrete. The steel temperature rises more slowly than that of a column without any concrete filling because of the heat sink effect of the concrete core. This is referred to as a capacitive method of fire protection.

It is believed that degradation of the concrete begins when the steel expands. With little or no tensile strength, unreinforced concrete can rupture into blocks along the length of the core leaving horizontal gaps. The addition of reinforcing bars or steel fibers helps to delay the start of this degradation. As the temperature increases in the concrete its strength also declines and is accompanied by the moisture in the concrete being driven off. A temporary reprieve of sorts is initiated when the moisture turns to steam, absorbing considerable quantities of heat. This steam needs to be released into the atmosphere to prevent a potential bursting hazard. Hence, vent holes have to be provided in the steel section as described in the following section.

In addition to providing confinement to the concrete core, the steel shell also protects the concrete from direct exposure to the heat source and prevents progressive spalling thus reducing the rate at which the concrete core degrades.

The addition of a 4 or 8-bar reinforcing cage with appropriately designed ties also provides confinement for the concrete core and thus enhances the fire endurance period for RC filled HSS columns. Protected first by the steel shell and then by the concrete cover, the temperature in the reinforcing bars increases slowly. However, it was found from the NRC studies (Lie and Kodur, 1996) that increasing cover beyond the minimum of 25 mm (1 in.) did little to increase the fire endurance period.

Steel fibers were also found to delay the degradation of the concrete core by providing confinement to the concrete and additional tensile strength. Predictably, load capacity was not increased significantly but the upper limit on fire endurance period increased to 3 hours as compared with 2 hours for PC-filling.

Another factor which influenced fire resistance was the shape of the HSS. Concrete-filled circular HSS columns have higher fire resistance as compared to that of concrete-filled square HSS columns of similar width. The corners of a square section behave like a fin protruding from the core. The concrete and any reinforcing steel in the corners degrade faster because heat can enter through multiple paths.

The NRC studies show that the slenderness of columns also have significant influence on the fire resistance. Lie and Chabot (1992) found that slender columns lose their load carrying capacity faster than do stocky columns. The capacity of slender columns can drop well below the resistance of the concrete core alone, C'_r. Although stocky circular HSS columns can maintain their strength above C'_r, occasions of sudden failure were observed in the test program. It was found that the fire resistance remains predictable and without sudden failure for loads up to 1.0 times C'_r for PC filling, 1.1 times C'_r for FC filling and 1.7 times C'_r for RC filling.

DESIGN FORMULA AND CURVES

Using the results from the NRC studies, the Canadian Steel Construction Council published three "Fire Protection Bulletins" (CSCC, 1994, 1997, and 1998), proposing a design method, suitable for inclusion in the NBCC (NRC, 1995), for each of the filling types. To facilitate the use of the NRC fire resistance equation by designers, who generally know what fire endurance period is required but need to know the axial load capacity of a member, Equation 1 was rearranged in terms of a maximum load for a desired fire-resistance rating. The proposed design method, which includes the three types of filling, is as follows:

Concentrically loaded HSS columns that are filled with plain, steel fiber-reinforced or bar-reinforced concrete and are fabricated and erected within the tolerances as stipulated in CAN/CSA-S16.1-94, "Limit States Design of Steel Structures" (CSA, 1994) shall be assigned a fire-resistance rating, R, provided:

$$C \le C_{max} \tag{2}$$

where

C = *axial compressive force due to dead and live loads in kN (kips), without load factors*

$$C_{max} = \left(\frac{a(f'_c + 20)\, D^{2.5}}{R\,(KL - 1{,}000)} \right)^2 (SI\ units) \tag{3}$$

$$= \left(\frac{34.9a\,(f'_c + 2.90)\, D^{2.5}}{R\,(KL - 3.28)} \right)^2 (U.S.\ Customary\ units)$$

Table 1. Values of Constant "a" in Equation 3

Aggregate type*	Filling type	Steel reinforcement	Circular columns	Square columns
S	PC	N/A	0.070	0.060
S	FC	≈ 2%	0.075	0.065
S	RC	1.5%-3%	0.080	0.070
S	RC	3%-5%	0.085	0.075
N	PC	N/A	0.080	0.070
N	FC	≈ 2%	0.085	0.075
N	RC	1.5%-3%	0.090	0.080
N	RC	3%-5%	0.095	0.085

* Type S concrete is made with siliceous coarse aggregate;
Type N concrete is made with carbonate coarse aggregate.

Table 2. Validity Limits (SI Units) for the Use of Proposed Equation 3

Parameters	Concrete Filling		
	Plain	Steel fiber-reinforced	Bar-reinforced
f_c' (MPa)	20 to 40	20 to 55	20 to 55
D (round) (mm)	140 to 410	140 to 410	165 to 410
D (square) (mm)	140 to 305	102 to 305	175 to 305
Reinforcement (%)	N/A	≈ 2% of the concrete mix by mass	1.5% to 5%, with limits on size, number and spacing of bars and ties in accordance with CSA A23.3
Concrete Cover (mm)	N/A	N/A	≥ 25
R (minutes)	≤ 120	≤ 180	≤ 180
KL (mm)	2000-4000	2000-4500	2000-4500
Class*	1, 2 or 3	1, 2 or 3	1, 2 or 3

* in accordance with CAN/CSA-S16.1-94

but shall not exceed 1.0 times C'_r for HSS columns filled with plain concrete, 1.1 times C'_r for HSS columns filled with steel fiber-reinforced concrete, and 1.7 times C'_r for HSS columns filled with bar-reinforced concrete, where C'_r is the compressive strength of the unreinforced concrete core

a = constant as specified in Table 1

f_c' = specified compressive strength of concrete in accordance with CSA A23.3, "Design of Concrete Structures," (CSA, 1994a), MPa (ksi)

D = outside diameter of a round HSS column or outside width of a square HSS column, mm (in.)

R = specified fire endurance period, minutes

KL = effective length of column as defined in CAN/CSA-S16.1, "Limit States Design of Steel Structures," (CSA, 1994), mm (ft), and subject to validity limits in Table 2 (SI units) or Table 3 (U.S. Customary units).

Notes for Figures 4(a) through 4(d):

Table 3. Validity Limits (U.S. Customary Units) for the Use of Proposed Equation 3

Parameters	Concrete Filling		
	Plain	Steel fiber-reinforced	Bar-reinforced
f_c' (ksi)	2.9 to 5.8	2.9 to 8.0	2.9 to 8.0
D (round) (in.)	5.5 to 16	5.5 to 16	6.5 to 16
D (square) (in.)	5.5 to 12	4.0 to 12	6.9 to 12
Reinforcement (%)	N/A	≈ 2% of the concrete mix by mass	1.5% to 5%, with limits on size, number and spacing of bars and ties in accordance with CSA A23.3
Concrete Cover (in.)	N/A	N/A	≥ 1.0
R (minutes)	≤ 120	≤ 180	≤ 180
KL (ft)	6.5-13.0	6.5-14.75	6.5-14.75
Class*	1, 2 or 3	1, 2 or 3	1, 2 or 3

* in accordance with CAN/CSA-S16.1-94

(1) C_r' is calculated in accordance with Clause 18.4 of CAN/CSA-S16.1-94 (CSA, 1994),

$$C_r' = 0.85 \, \phi_c f_c' A_c \lambda_c^{-2} \left[\sqrt{1+0.25\lambda_c^{-4}} - 0.5\lambda_c^{-2} \right]$$

where

$\phi_c = 0.60$

f_c' = compressive strength of concrete, MPa (ksi)

A_c = area of concrete, mm²(in.²)

$$\lambda_c = \frac{KL}{r_c} \sqrt{\frac{f_c'}{\pi^2 E_c}}$$

KL = effective length of column, mm (in.)

r_c = radius of gyration of the concrete area

E_c = initial elastic modulus for concrete, considering the effects of long-term loading

= $(1+S/T) \, 2500 \sqrt{f_c'}$ for normal weight concrete, where f_c' is expressed in MPa, or

= $(1+S/T) \, 952 \sqrt{f_c'}$ for normal weight concrete, where f_c' is expressed in ksi, S is the short-term load and T is the total load on the column.

Column design curves have been derived based on $S/T = 0.25$. Confinement effects are ignored.

(2) HSS designations and dimensions are as given in the CISC Handbook of Steel Construction (CISC, 1995).

(3) Two unobstructed vent holes, each not less than 12.7 mm (0.5 in.) in diameter shall be provided at opposite ends of the column and at each intermediate floor to vent steam. The holes shall be located 150 mm (6 in.) from a base plate, cap plate or concrete slab. Pairs of holes should be oriented such that adjacent pairs are perpendicular (Kodur and Lie, 1995b).

In the above design method, the fire resistance is expressed in terms of structural design parameters. This offers a convenient method of integrating the fire resistance design with structural design. Using these equations, a designer can arrive at a desired fire resistance value by varying different structural parameters, such as length, load, diameter (width), and concrete strength. The use of these equations leads to an optimum design that is not only economical but is also based on rational design principles.

In order to make the design process simpler, the CSCC "Fire Protection Bulletins" (CSCC, 1994, 1997, and 1998) also contain design charts, for different fire resistance ratings, wherein C_{max} is plotted as a function of effective length for various column dimensions and concrete strengths. Figure 4 shows four such design graphs for circular and square HSS columns and having a 2 and 1 hour fire resistance rating. For HSS commonly available in Canada, the C_{max} for concrete strengths of 30 MPa and 50 MPa can be read from the design charts.

The design method for concrete-filled HSS columns can easily be programmed into an electronic spreadsheet, and with only the dimensions of the HSS needed to calculate geometry, the designer can utilize Equation 2 directly.

The design method specified above and related design curves dealing with PC-filled HSS columns has been incorporated into Appendix D of the 1995 version of the National Building Code of Canada (NBCC)(NRC, 1995). Appendix D provides conservative methods for calculating the fire resistance of building components as an alternative to using furnace testing. For the other types of concrete fillings, the revised design method is being submitted for the 2001 version of the NBCC. Similarly, ASCE/SFPE 29-99, "Standard Calculation Methods for Structural Fire Protection"
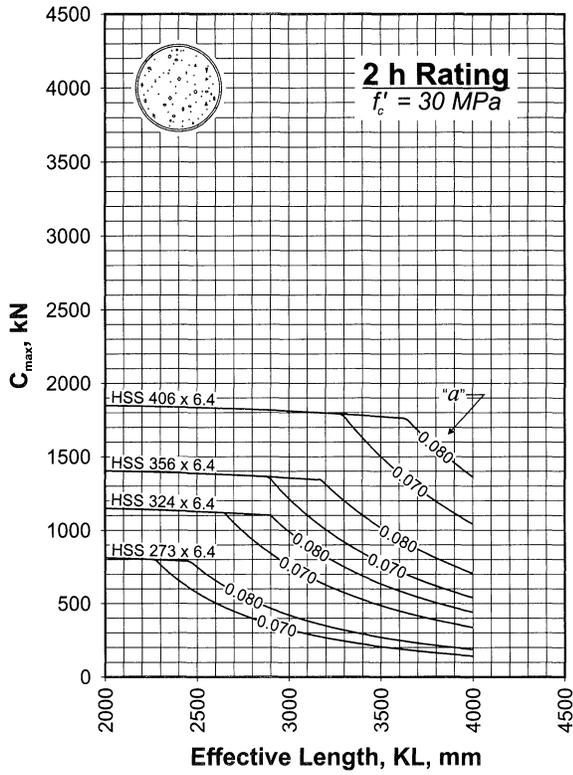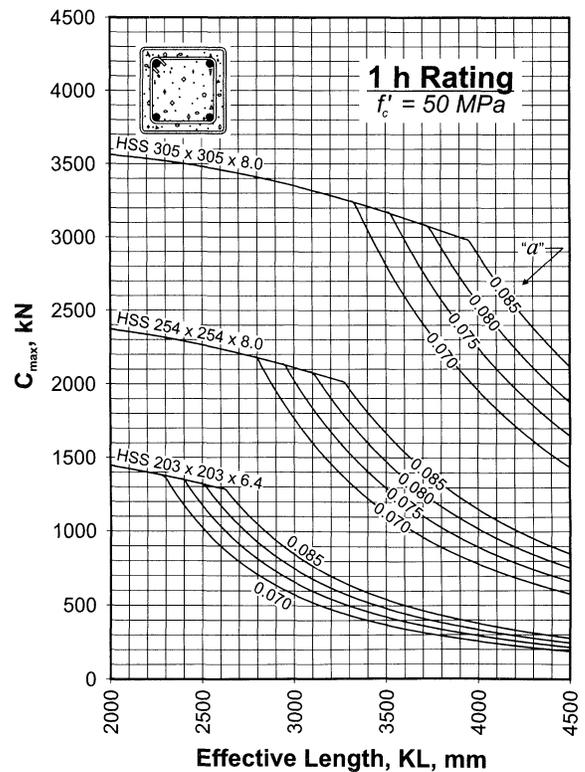
(a) Plain
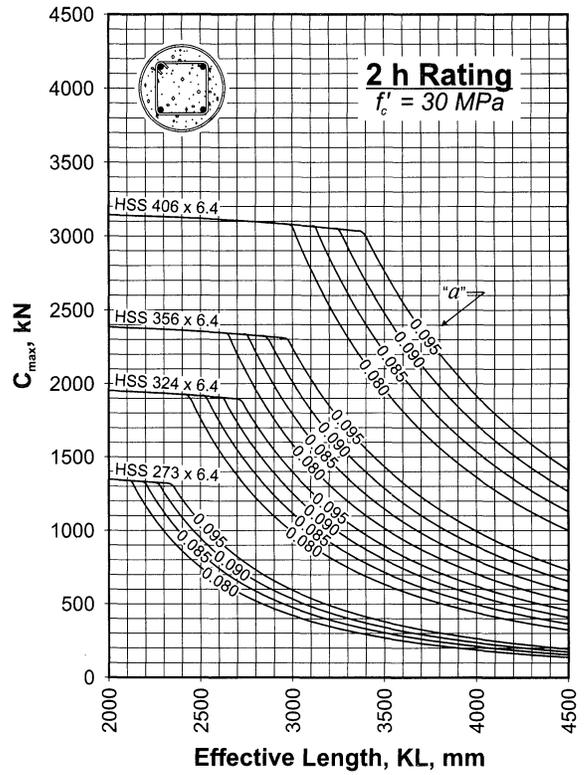
(b) Bar-reinforced
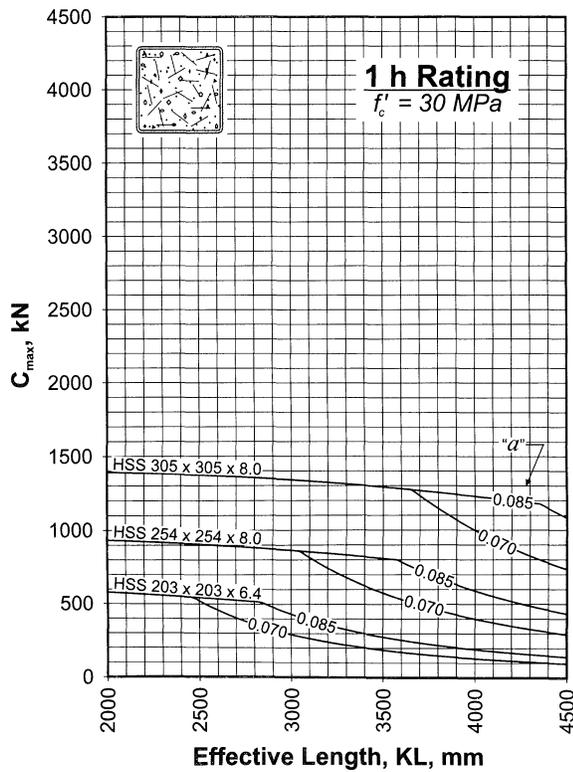
(c) Steel fiber-reinforced

(d) Bar-reinforced

Fig. 4. Fire resistance design graphs for concrete-filled HSS columns.

(ASCE/SFPE, 1999), incorporates the design method for PC-filled HSS columns. It is expected that this Standard will be referenced by model building codes in the United States as an alternative to furnace testing. Equations corresponding to the other two concrete fillings will be proposed for the next edition of this Standard.

To assist designers and constructors in the use of concrete-filled HSS columns, the National Research Council, in collaboration with the Canadian Steel Construction Council, is developing a Design Guide, to be published in 2000, which will aid in the fire resistance design of these columns.

DESIGN AND CONSTRUCTION CONSIDERATIONS

Some designers are under the impression that concrete-filled HSS columns are protected from fire by the heat sink effect of the concrete filling. This view is not only incorrect, but also a dangerous misconception. The behavior of concrete-filled HSS columns in a fire has been described above and detailed elsewhere. The shedding of load from the steel shell to the concrete core, which eventually carries most of the axial load, means that the designer must pay attention to methods of loading and other practical details not considered in the normal course of structural design. This section lays out some guidance on the design and construction of concrete-filled HSS columns.

Eccentric loading

The design method proposed above is based on the assumption of axial loads on the column. A few tests have been carried out at the NRCC (Lie and Chabot, 1992 and Kodur and Lie, 1995) on eccentrically loaded columns but with relatively small eccentricities. Although it is unlikely that the proposed design method would be suitable for beam-column design, small moments could be accommodated. Since concrete-filled HSS columns are generally used to carry only gravity loads, any bending moments present are due to unbalanced loads and if sufficiently small, could either be neglected or assumed to be resisted by a heavier walled section. If longer fire endurance periods are necessary or larger moments are present, higher bending resistance could be achieved by adding additional bar-reinforcement. In any case, combined axial load and bending should be checked at ambient temperature using methods for composite columns found in CSA (1994) and AISC (1993).

HSS wall thickness

The thickness of the HSS wall was not found to have significant influence on the fire endurance of concrete-filled HSS columns. Consequently, neither the wall thickness nor the area of steel section is a parameter in the proposed design method above. In fact, using a wall thickness greater than that required to ensure that the HSS is at least a class 3 section in

bending (compact section), reduces the load carrying capacity for a given fire endurance period. Increasing the wall thickness reduces the size of the concrete core, which is the dominating parameter. In general, it is more economical to keep wall thickness to a minimum unless other factors such as connection details dictate otherwise.

Load application and connections

In the furnace tests, the axial load was applied through a sizeable cap plate and the reactions taken out through a matching base plate. The Canadian and US steel design standards (CSA, 1994 and AISC, 1993), require direct bearing of load and reaction at the top and bottom of a composite column. Direct bearing insures that loads are distributed between the steel shell and the concrete core immediately and, without reliance on friction or mechanical bond at the steel-concrete interface, to transfer longitudinal shear. In a fire situation, the steel and concrete are expanding at different rates and the steel shell softens, shedding load. It would be unwise to rely on friction or mechanical bond under these circumstances.

However, the Canadian standard (CSA, 1994) now allows horizontal members to be framed into the column at intermediate floors. Although no guidance is given on the transfer of load, it would be prudent for the designer to check that the steel section is capable of carrying the additional load until a portion can be transferred into the concrete through friction (mechanical bond is too variable and should be ignored). The question is, should this connection also be allowed in a fire situation? If a fire on a lower level heats the column at that level, the authors believe that the ability of the steel-concrete
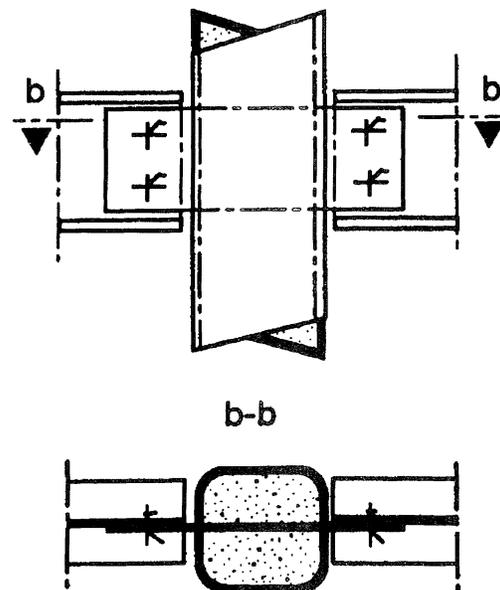

Fig. 5. Thorough plate connection between column and beams.

interface to transfer the load into the concrete is doubtful. An alternate load path, up the cooler steel of the level above and into the concrete core is possible but not proven. An alternative is to use a through plate connection as illustrated in Figure 5 to help transfer loads into the core at ambient temperatures and during a fire.

Steam venting

When concrete-filled HSS columns are exposed to fire, water is driven from the concrete and heat energy is absorbed as it turns to steam. This has some influence on the fire endurance period of the composite column but also presents a potential bursting hazard if the steam is not released to the atmosphere. The recommended number, size, location and configuration of the vent holes as illustrated in Figure 6 and described earlier, is based on the experimental studies at NRC (Lie and Chabot, 1992; Chabot and Lie, 1992; and Kodur and Lie, 1995). The designer must ensure that the vent holes will not be blocked or covered by poured slabs, concrete block, and wall, window or door frames. The vent holes may be blocked during the concrete placing stage, but the blocking can be removed once the concrete has set. The concrete protruding from the vent holes can be smoothed and painted to blend with the finish on the exposed steel as desired.

Concrete filling methods

Concrete filling of HSS columns requires no special equipment and the filling operation may be integrated into other
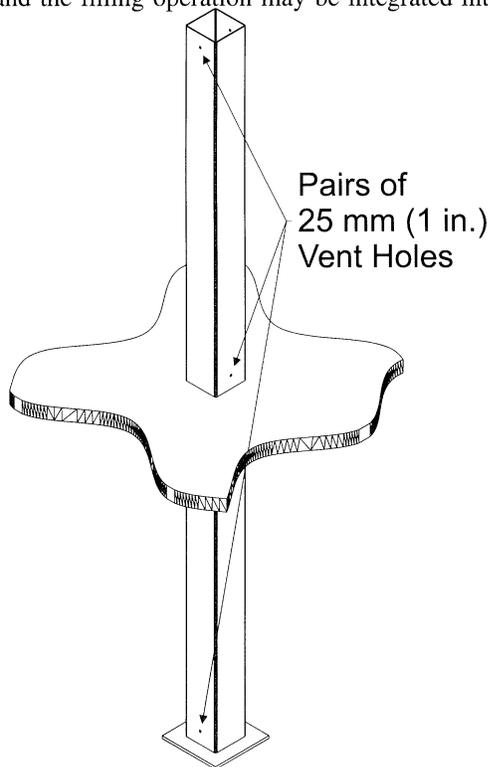

Pairs of 25 mm (1 in.) Vent Holes

Fig. 6. Steam vent hole locations.

concreting operations. Typically, the concrete is placed into the HSS column after it has been erected and temporarily braced. Temporary bracing is usually required because attached beams are in direct bearing and concreting must take place before they can be erected. A working platform is suspended from the top of the column and a hopper with elephant's trunk type chute lead into the top of the HSS column. The same crane doing the erection can hoist the concrete bucket. Normal good practice for concrete placing, including drop heights and consolidation through vibrating, has to be followed. Care must be taken to eliminate or minimize the gap between the top of the concrete core and the underside of the cap plate.

If many columns are to be filled, contractors can set-up an area where they can be filled in groups either in vertical or inclined positions. One potential problem with inclined pouring is control of the gap between concrete and cap plate. Concrete pumping can be used either from the top or the bottom. It has been suggested that concrete could be pumped through a hole at the bottom of the column while air is forced out through the already required vent holes at the top. This approach would simplify co-ordination of trades considerably by allowing the steel frame to be fully erected and plumbed before concreting took place.

CASE STUDIES

Concrete-filled HSS columns have been used primarily in schools and other assembly type occupancies in two and three story buildings where structural fire protection is required. Interior columns supporting mezzanines and exit stairwells is another common application. In jurisdictions where non-combustible roofs must also be protected, concrete-filled HSS columns are also useful for fire protection in one story buildings. This section describes three such existing buildings where PC-filled and RC-filled HSS columns have been used.

Museum of Flight, Seattle, Washington

The Museum of Flight at King County Airport is the largest air and space museum on the west coast of the United States and is home to one of the most extensive aircraft collections in the world (Kodur and Lie, 1995b). The 13,300 m² (143,200 ft²) museum is dominated by a six-story-high "Great Gallery," (Figure 7) constructed as part of a three-part extension, and is composed of a main steel-and-glass exhibit hall, a library, a 268-seat auditorium, and office and conference space. The irregularly shaped building is 148 m (185 ft) long, 76 m (250 ft) wide, and 23 m (75 ft) high.

The architectural requirement for natural light, to see the sky behind the aircraft suspended from the ceiling and the desire to see the exhibits from the outside lead to a glass enclosure supported by a three-dimensional steel frame. Further, the framing members had to be thin so as not to distract from the exhibits, and not to generate any visible noise. HSS

were recommended by the structural engineers for the columns. The Authority Having Jurisdiction (AHJ) had adopted the Uniform Building Code (ICBO, 1997) which required a 60 minute fire resistance rating for the columns supporting the roof. To avoid the bulk and appearance of sprayed on fire protection, as well as to realize the beauty of the exposed steel, concrete-filling was adopted. Further, to minimize the size of the columns to 203 mm (8 in.) diameter, reinforcing bars were added to increase the loading carrying capacity at the specified fire endurance period.

Although the UBC did not specifically recognize the concept of concrete-filled HSS, the AHJ accepted the test data and analytical work done by the National Research Council (NRC). Using the same mathematical model developed to conduct the simplified design equations above, the NRC study showed that the RC-filled HSS columns could provide a fire resistance rating of 60 minutes or higher under full design loads (Kodur and Lie, 1995b).

St. Thomas Elementary School, Hamilton, Ontario

Owned by the Hamilton-Wentworth Roman Catholic Separate School Board, St. Thomas Elementary School is a typical two-story building with an interconnected floor. The open area contains two staircases and is covered with a glass dome (Figure 8). The natural light and slender members give the space an airy look. To conform to the Ontario Building Code (Government of the Province of Ontario, 1990), the designers required the columns to have a one hour fire resistance rating. NRC was called upon to use their analytical techniques, and provided solutions using both square and round HSS with different concrete strengths (Kodur and Lie, 1995b). The designers selected the more elegant round HSS 406 (16 in.) columns and adopted RC filling for the ground level columns, in order to carry higher loads, and PC filling for second story columns supporting the roof.

Correctional Facility

The correctional facility shown in Figure 9 is located in the Canadian prairies. It employs a concrete-filled 168 mm (6.6 in.) diameter HSS column in a predominantly concrete building to minimize the view restrictions from the guard's control room and provide the 2 hour fire resistance rating required for an Institutional Building with restrained occupants. A concrete column or structural steel column with conventional sprayed or membrane fire protection would have greatly reduced the site lines. In addition, external fire protection materials could be removed by inmates thus eliminating the members fire resistance and exposing it to attack by fire.

Fig. 7. "Great Gallery", Museum of Flight.

Fig. 8. Entrance of St. Thomas Elementary School.

SUMMARY

Concrete filling offers a practical solution for providing fire protection to HSS columns without any external protection. Results from the experimental and numerical studies indicate that any amount of fire resistance, in the practical range for building construction, can be obtained for HSS columns through three types of concrete filling. The use of fire resistance design equations leads to an optimum design that is not only economical but is also based on rational design principles.

As illustrated in Case Studies, concrete-filled HSS columns are being successfully used, and recognition of the proposed design method by Building Code development groups through direct adoption or preferably, through referenced standards will lead to much wider use of this efficient composite construction system.

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