BULLETIN No. 25

Fire Protection

CANADIAN STEEL CONSTRUCTION COUNCIL

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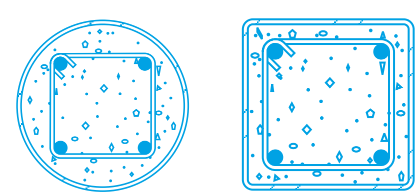
FIRE RESISTANCE OF BAR-REINFORCED CONCRETE-FILLED STEEL HSS COLUMNS

INTRODUCTION

The National Research Council of Canada (NRCC), in a joint effort with the Canadian Steel Construction Council (CSCC), and with support from IPSCO Inc. and the American Iron and Steel Institute (AISI), has recently completed the second phase of the ongoing research programme studying the fire resistance of steel HSS (Hollow Structural Sections) columns filled with concrete.

The first phase of the project studied the behaviour of concentrically loaded, round and square HSS columns filled with plain concrete (without reinforcing) and was the subject of Fire Protection Bulletin #21. The design formula and curves were subsequently published in Appendix D of the 1995 National Building Code of Canada which gives guidance on the calculation of fire-performace ratings.



The present study introduces bar-reinforcing as a means of obtaining higher load capacities and longer fire endurance periods. Research staff at the Institute for Research in Construction (IRC), with the assistance of former CSCC Steel Fellows, have published a number of reports [References 1, 2 and 3] describing the results of a large number of loaded, full scale tests and in-depth analytical studies.

TEST PROGRAMME

The work on concentrically loaded HSS columns filled with bar-reinforced concrete was completed in 1995 and a paper entitled 'Fire Resistance of Steel Columns Filled with Bar-Reinforced Concrete', co-authored by T.T. Lie and V.K.R. Kodur was published in the ASCE Journal of Structural Engineering in January 1996 [Reference 4]. The results of 29 full scale column tests were used to verify a numerical model which incorporated realistic stress-strain relationships and the thermal properties for structural steel, concrete, and reinforcing steel at elevated temperatures [References 5 and 6]. Using the model, computer simulated fire tests were conducted to determine the influence of various factors on the fire resistance. The results were used to develop a simplified expression for design.

COLUMN BEHAVIOUR

At room temperature, the axial load in the column is shared between the concrete core and steel section, and shifts primarily to the concrete core at elevated temperatures with the steel section providing confinement. Factors which influence the fire resistance and load capacity of concrete-filled HSS

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DESIGN FORMULA AND CURVES

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

$C \leq C_{max}$

where

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

$$C_{max} = \left(\frac{a \left(f_c' + 20 \right) D^{2.5}}{R \left(KL - 1000 \right)} \right)^2$$

but shall not exceed 1.7 times the factored compressive resistance of the concrete core, C_r', in accordance with CAN/CSA-S16.1,

a = *constant (See Table 1)*

f_c' = *specified compressive strength of concrete in accordance with CSA-A23.3, "Design of Concrete Structures," MPa,*

D = *outside diameter of a round column or outside width of a square column, mm,*

R = *specified fire endurance period, min,*

KL = *effective length of column as defined in CAN/CSA-S16.1, mm;*

subject to validity limits:

f_c' *20 MPa to 55 MPa,*

D *165 mm to 410 mm for round columns, 175 mm to 305 mm for square columns,*

longitudinal reinforcement shall be 1.5% to 5%, with limits on size, number and spacing of bars and ties in accordance with CSA A23.3,

25 mm concrete cover to longitudinal reinforcing bars,

R *≤ 180 minutes,*

KL *2000 mm to 4500 mm, and the hollow steel sections shall be Class 1, 2 or 3 in accordance with CAN/CSA-S16.1.*

Table 1-Values of a

Aggregate type*	Steel reinforcement	Circular columns	Square columns
S	1.5%-3%	0.080	0.070
S	3%-5%	0.085	0.075
N	1.5%-3%	0.090	0.080
N	3%-5%	0.095	0.085

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

For hollow structural sections commonly available in Canada, C_{max} for concrete strengths of 30 MPa and 50 MPa may be read from Figures 1 to 6.

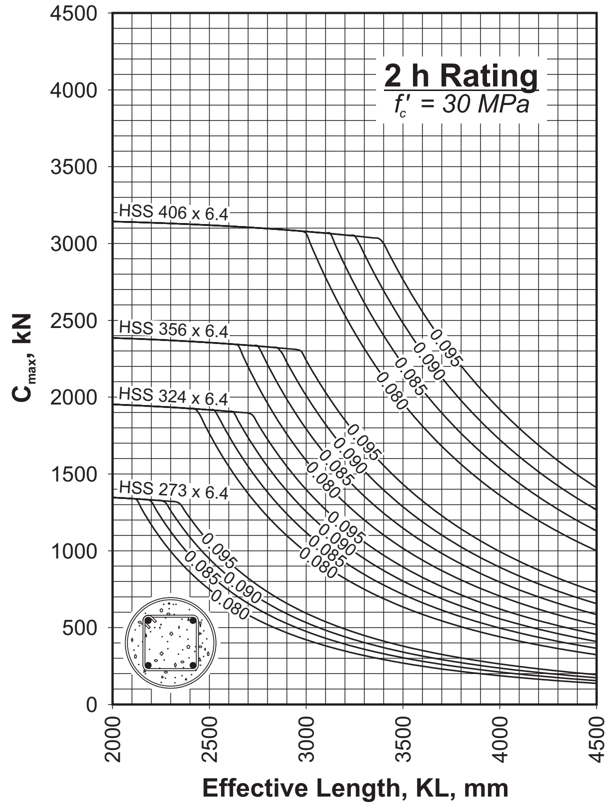

Figure 1: Round hollow steel columns with 30 MPa concrete and requiring a 2 h fire endurance period

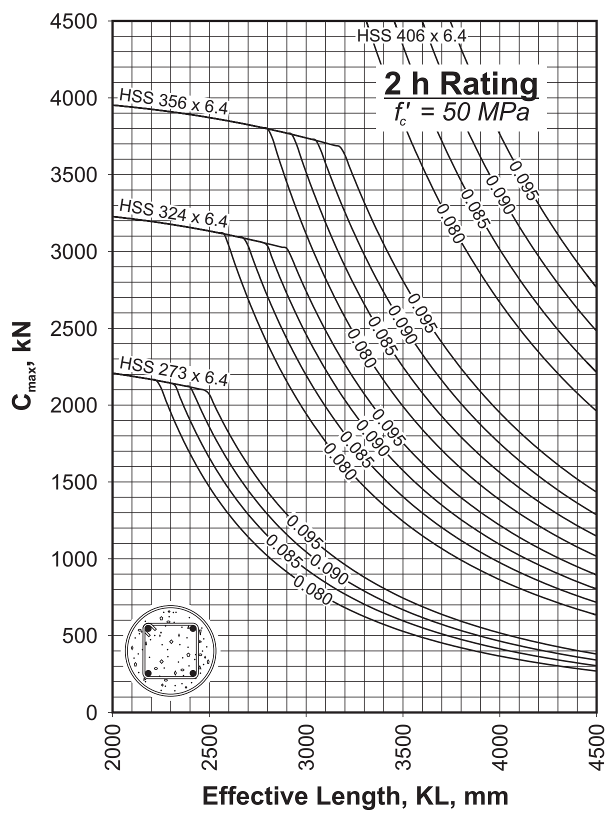

Figure 2: Round hollow steel columns with 50 MPa concrete and requiring a 2 h fire endurance period

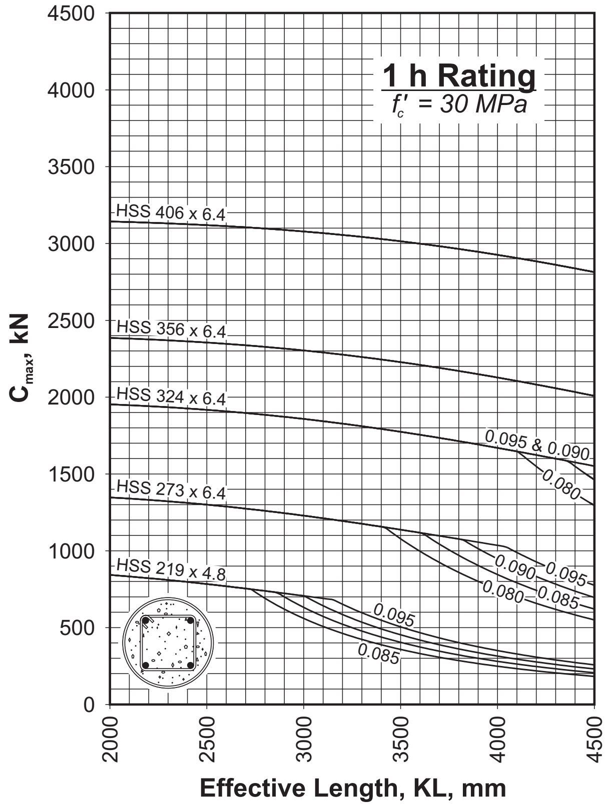

Figure 3: Round hollow steel columns with 30 MPa concrete and requiring a 1 h fire endurance period

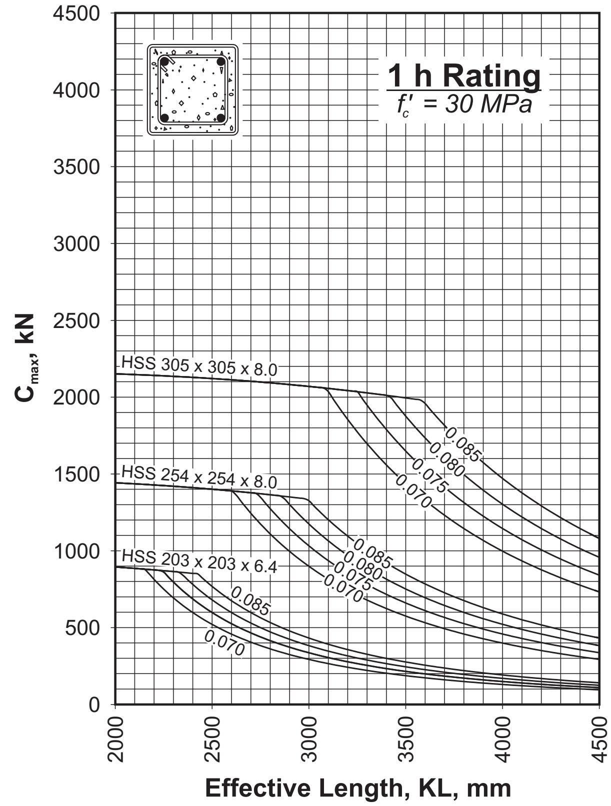

Figure 5: Square hollow steel columns with 30 MPa concrete and requiring a 1 h fire endurance period

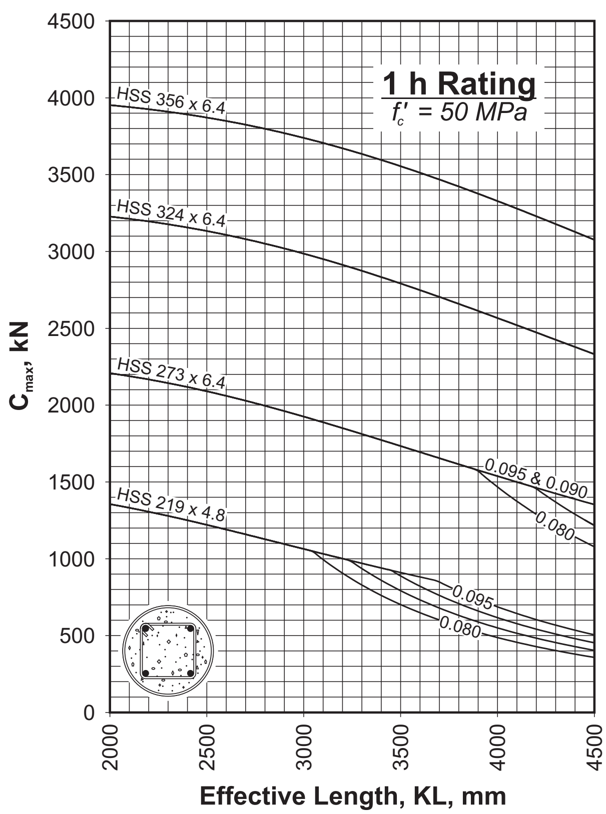

Figure 4: Round hollow steel columns with 50 MPa concrete and requiring a 1 h fire endurance period

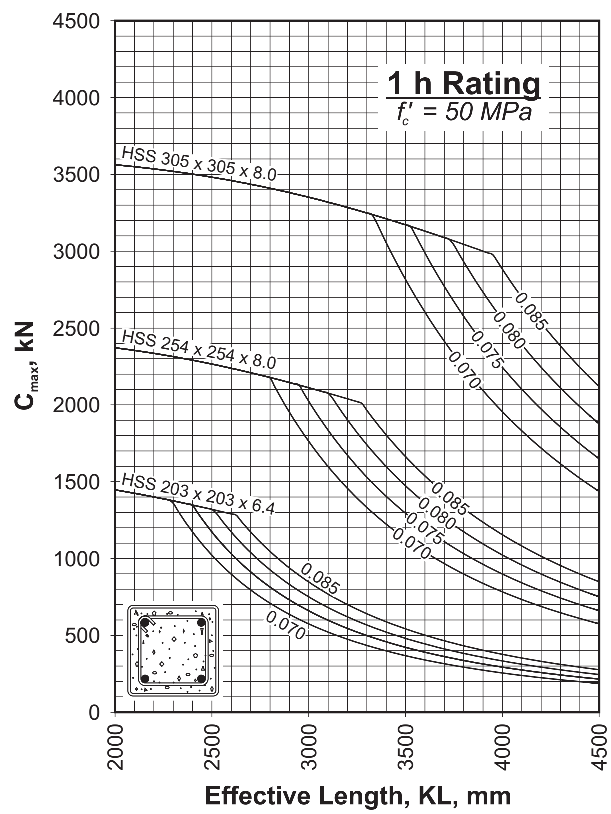

Figure 6: Square hollow steel columns with 50 MPa concrete and requiring a 1 h fire endurance period

columns in general include cross-sectional dimensions, length, concrete strength, and type of concrete aggregate. A general discussion of behaviour can be found in Fire Protection Bulletin #21. The discussion here is limited to the two new parameters introduced in the current study; percentage of reinforcing steel and concrete cover thickness to the reinforcing bars.

Three percentages of steel reinforcement, 1.5%, 3%, and 5%, representing low, medium and high levels of reinforcing were investigated. Although the fire resistance increased very little with increasing percentage of reinforcement, its presence provides additional containment for the concrete core at elevated temperatures, and substantially increases the duration of exposure to fire and the load carrying capacity of the column when compared to plain concrete-filled columns. Fire-resistance ratings of up to 3 hours can be achieved with bar-reinforcing.

Two values of cover thickness were investigated, 20 mm and 50 mm. The study found that increasing concrete cover beyond the minimum has little effect on fire endurance or load capacity. For simplicity, the minimum cover thickness has been assumed.

Tests [Reference 1] and comparisons with calculated fire resistances [Reference 5] showed that the fire resistance remains predictable and without sudden failure for loads up to 1.7 times the resistance of the unreinforced concrete core, C_r', and for effective column lengths up to 4500 mm.

At elevated temperatures, the moisture present in the concrete core turns to steam. A potential bursting hazard exists if the steam it is not released into the atmosphere. To prevent catastrophic failure, vent holes as described in Note 3 must be provided.

DESIGN FORMULA

The current study, as well as the previous study, concluded that the fire-resistance rating of a bar-reinforced concrete-filled HSS column is primarily a function of its size, slenderness ratio, concrete strength and type, percentage of reinforcing, and the load (unfactored) that it is supporting [Reference 7]. The design formula, expressed in terms of a restricted column load for a desired fire-resistance rating, is given on page 2. The text is patterned after Article D-2.6.6. in the 1995 NBCC to convey the approach for bar-reinforced concrete-filled HSS columns that will be proposed for the 2001 NBCC. The design curves given on pages 2 and 3 were constructed using the proposed formula for a series of round and square hollow steel sections. The following notes apply:

Notes to Figures 1 through 6:

(1) C_r' is calculated in accordance with Clause 18.4 of CAN/CSA S16.1-94 assuming normal-weight concrete, and S/T=0.25 where S is the short-term load on the column and T is the total load on the column. Confinement effects are ignored by setting $\tau = \tau' = 1.0$. [Reference 8]

(2) HSS designations and dimensions are in accordance with CAN/CSA-G312.3, and are given in the CISC Handbook of Steel Construction [Reference 9].

(3) Two unobstructed vent holes, each not less than 12.7 mm 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 from a base plate, cap plate or concrete slab. Pairs of holes should be orientated such that adjacent pairs are perpendicular [Reference 10].

REFERENCES

1. Chabot, M. and Lie, T.T., “Experimental Studies on the Fire Resistance of Hollow Steel Columns Filled with Bar-Reinforced Concrete”, IRC Internal Report No. 628, National Research Council of Canada, Institute for Research in Construction, Ottawa, Ontario, 1992.
2. Lie, T.T. And Denham, E.M.A., “Factors Effecting the Fire Resistance of Square Hollow Steel Columns Filled with Bar-Reinforced Concrete”, IRC Internal Report No. 650, National Research Council of Canada, Institute for Research in Construction, Ottawa, Ontario, 1993.
3. Lie, T.T. And Denham, E.M.A., “Factors Effecting the Fire Resistance of Circular Hollow Steel Columns Filled with Bar-Reinforced Concrete”, IRC Internal Report No. 651, National Research Council of Canada, Institute for Research in Construction, Ottawa, Ontario, 1993.
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6. Lie, T.T. and Irwin R.J., “Fire Resistance of Rectangular Steel Columns Filled with Bar-Reinforced Concrete”, ASCE Journal of Structural Engineering, Volume 121, No. 5, May 1995, pp. 797-805.
7. Kodur, V.K.R. and Lie, T.T., “Fire Performance of Concrete-Filled Hollow Steel Columns”, Journal of Fire Protection Engineering, Volume 7, No. 3, 1995, pp. 89-98.
8. Canadian Standards Association, ”Limit States Design of Steel Structures”, CAN/CSA-S16.1-94, Rexdale, Ontario, 1994.
9. Canadian Institute of Steel Construction, ”Handbook of Steel Construction”, Sixth Edition, Willowdale, Ontario, 1995.
10. Lie, T.T. and Kodur, V.K.R. , “Fire Protection of Hollow Steel Columns Through Concrete Filling”, Proceedings, CSCE Annual Conference, Volume 3, 1995, pp. 215-224.