Numerical studies on HSC-filled steel columns exposed to fire

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ABSTRACT: In recent years, the use of Hollow Structural Section (HSS) steel columns filled with high strength concrete (HSC) is becoming more popular due to numerous advantages they offer over traditional columns. Apart from the aesthetic point of view, this composite system offers structural advantages. The concrete filling improves the load-bearing capacity at ambient temperature and can significantly enhance the fire endurance of the column. However, while the design rules for steel columns filled with normal strength concrete (NSC) are well established, there are many uncertainties for the filling with HSC. Thus, a numerical study is performed using the computer program 'BoFIRE' to investigate the behavior of HSS steel columns filled with HSC at both room and elevated temperatures. The test variables included column slenderness, load eccentricities, concrete compressive strength and cross-sectional shape.

1 INTRODUCTION

The concrete filling of Hollow Structural Section (HSS) steel columns has two main beneficial effects. At ambient temperature, the load-bearing capacity is significantly increased. Thus, it is possible to reduce the dimensions of the cross-section, which results in enhanced usable space in the building. Under fire load, the advantageous thermal properties of concrete lead to increased fire endurance. Therefore additional external fire protection for the steel might be superfluous.

Though the fire performance of HSS columns filled with NSC is well established (Kodur & Lie 1995; Kodur & MacKinnon 2000), there are many uncertainties for HSC-filled steel columns (Kodur 1998; Kodur & McGrath 2003). This is mainly attributed to the material properties of HSC at elevated temperatures that are not that well established. Therefore two different approaches dealing with HSC were considered for the numerical analysis of HSS columns. These are the Canadian provisions according to the standard CAN/CSA-S16-01 and to the work of the researchers Kodur & Sultan (2003) as well as Cheng, Kodur & Wang (2004). In addition, the European material properties according to the codes Eurocode 2, part 1-2 (prEN 1992-1-2) for concrete structures and Eurocode 4, part 1-2 (prEN 1994-1-2) for composite structures were considered.

The provided material models were implemented in the FEM program 'BoFIRE'. A series of parametric studies were carried out on typical HSC-filled HSS steel columns to investigate their behavior at both ambient and elevated temperatures. The studies included the column slenderness, load eccentricities, concrete compressive strength and cross-sectional shape.

2 COMPUTER PROGRAM 'BOFIRE'

All parametric studies were carried out using the transient, non-linear, incremental computer code 'BoFIRE'. This computer program is based on the finite element formulation and written by Schaumann (1984) and further developed by Upmeyer (2001) and Kettner (2005). It is capable of predicting thermal and structural behavior of both steel and composite structures exposed to fire. The program is based on the following principle:

$$R(t) \geq S(t) \tag{1}$$

where R(t) = resistance at time t; S(t) = effect of mechanical action at time of fire exposure t.

The load-bearing capacity of structures R(t), which are charged by a mechanical load S(t) while exposed to fire, depends on the modification of the material properties, such as decreasing of strength and elastic modulus affected by heat. Thus, the procedure for determining the remaining bearing capacity of structures is based on a numerical calculation model coupling the thermal and mechanical response at various time steps.

At first the thermal response takes place. In this stage, the fire temperature and the temperature distribution of the cross-section are computed. According to the temperature distribution, the modification of the material properties caused by temperature can be computed. Subsequently, the mechanical response is calculated where deformation and remaining strength of the members are determined. These results are compared to the applied load on the column and it is verified whether the structure still has sufficient load-bearing capacity. This procedure is repeated for various time steps until the resistance of the member is less than the applied load, which represents failure of the column. The duration to failure is taken as the fire resistance period of the column.

2.1 Thermal response

In 'BoFIRE', the temperature field is calculated using the Fourier differential equation for heat conduction:

$$-\operatorname{div}\left(\lambda \times \operatorname{grad}\theta\right) + c \times \rho \times \dot{\theta} - f = 0 \tag{2}$$

where λ = thermal conductivity; θ = temperature; c = heat capacity; ρ = density; $\dot{\theta}$ = derivation of temperature with respect to time; f = heat source.

Caused by the modifications of material properties due to heat exposure, the differential equation becomes transient since the temperature field gets inhomogeneous. Thus, that equation has to be solved numerically. In the following, the basis of that method will be described according to Kettner (2005).

A mathematical transformation of Equation 2 results in the weak formulation of the differential equation:

$$\int_{\Omega} \lambda \times \operatorname{grad}\theta : \operatorname{grad}\delta\theta \, dA + \int_{\Gamma} q \times \delta\theta \times n \, dS + \ldots$$
$$\ldots + \int_{\Omega} \rho \times c \times \dot{\theta} \times \delta\theta \, dA = 0 \tag{3}$$

where Ω = area; Γ = boundary of considered area; q = heat flux; n = normal vector on the boundary.

For the solution of the weak form, bi-linear shape functions on a four node isoparametric element according to Equation 4 are used.

$$N_i = \frac{1}{4} \times \left(1 \pm \eta\right) \times \left(1 \pm \xi\right) \tag{4}$$

The approach is presented on the left side of Figure 1. An example for mesh generation with BoFIRE is shown at the right side of Figure 1. Moreover, the computer program 'BoFIRE' also recognizes different material properties as a function of temperature including that of fire protection materials.
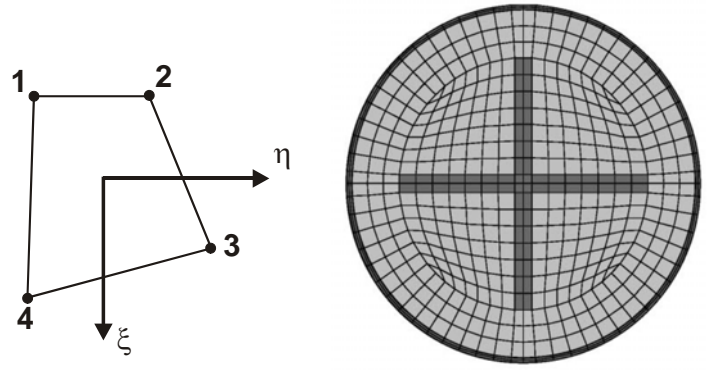

Figure 1. Four node isoparametric element (left) and mesh for a concrete-filled HSS column with embedded X-shape profile (right).

2.2 Mechanical response

It is possible to calculate all types of cross-sections and linear structures as beams, columns or plane frames taking second order theory into account. The calculation is based on the Bernoulli hypothesis for plain state of strains. Shear deformations are not considered.

Due to the nonlinear material properties, cross-sectional values and internal forces depend on the temperature field and strains into the cross-section. The strains are calculated by the balance of internal and external forces. The solution of the incremental system equation is given by Schaumann (1984):

$$\Delta \underline{S}_L - \Delta \underline{S}_{th} = \left(\underline{K}_t^I - \underline{K}_{t_0}^I\right) \times \underline{v}_{t_0} + \Delta \underline{K}^{II} \times \underline{v}_{t_0} + \ldots$$
$$\ldots \left(\underline{K}_t^I + \underline{K}_t^{II}\right) \times \Delta \underline{v} \tag{5}$$

where $\Delta \underline{S}_L$ = difference between external forces per time increment; $\Delta \underline{S}_{th}$ = difference between thermal strains per time increment; $(\underline{K}_t^I - \underline{K}_{t0}^I) \times \underline{v}_{t0}$ = difference of system matrix stiffness (elastic portion); $\Delta \underline{K}^{II} \times \underline{v}_{t0}$ = difference of system matrix stiffness (geometric portion according to second order theory); $(\underline{K}_t^I + \underline{K}_t^{II}) \times \Delta \underline{v}$ = difference of deformations per time increment.

At first, the internal force variables and deformations caused by the external forces $\Delta \underline{S}_L$ are computed in one or more increments. In a parallel calculation the temperature field is established as previously described. Because of the incremental procedure it is possible to linearize the influence of non-linear material behavior and temperature distribution.

3 HSC MATERIAL PROPERTIES

The carried out investigations are based on both Canadian (CAN3-A23.3-M94) and European HSC material properties. The considered codes show differences regarding mechanical as well as thermal properties. Because of its importance for the compu-

tation of heated cross-sections, the stress-strain relationship at elevated temperatures is compared. The investigation is carried out for the case of HSC-filling with siliceous aggregate concrete of 60 MPa strength. To show the characteristics, the ascending branch of the stress-strain relationships is presented only for 100°C and 600°C in Figure 2 according to the code regulations. It is obvious that the Canadian regulations are more conservative since the peak stress is significantly reduced for temperature of 100°C. In contrast to this, the European code prEN 1992-1-2 does not diminish the peak stress for the same temperature. This is also true for temperature of 200°C, which is not presented in Figure 2. For greater temperature of 600°C, the peak stress according to both codes is almost equal. However, the Canadian code assumes a far more brittle HSC behavior since the strain at peak stress is less than the corresponding European value. The differences for other temperatures are less pronounced and thus not presented.
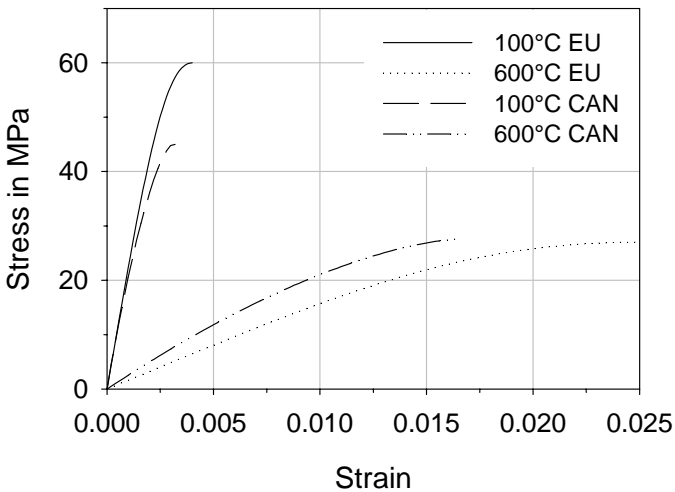

Figure 2. Comparison between Canadian (CAN) and European (EU) stress-strain relationship at elevated temperatures.

4 EFFECT OF SECTION SIZE

A massive column will show an improved fire resistance over a leaner column (Lie & Kodur 1996), which is expressed in the A/V-ratio, where 'A' is the area of the surface and 'V' is the volume of a member both per unit length.

To illustrate the effect of section size on fire resistance of concrete-filled HSS columns, a parametric study was carried out on ten different circular HSS columns filled with HSC. For excluding effects of slenderness, the selected columns have a length of only 0.50 m (short columns) with fixed-fixed end conditions. The yield strength of the steel tube is assumed to be 235 MPa. As filling, concretes with cylindrical compressive strength of 40, 60 or 90 MPa with calcareous aggregates are chosen. These strengths are equivalent to 50, 75 and 105 MPa based on cube strength of concrete as measured in Europe. The steel sections were selected such that

they contribute about one third to the total load-bearing capacity at room temperature. The calculation is carried out with material properties according to Eurocodes and a load level of 50% at room temperature. The interrelationship between the fire resistance period of a column and its A/V-ratio is apparent in Figure 3.
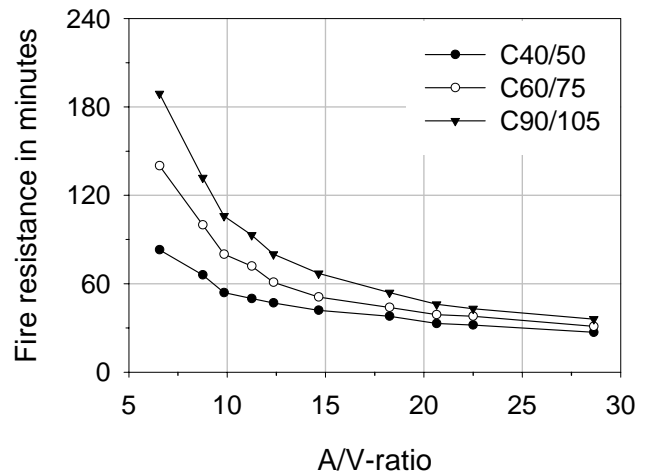

Figure 3. Effect of A/V-ratio on fire resistance period of HSC-filled HSS columns.

It is obvious that a column with low A/V ratio exposes a relatively small surface to the fire delaying its heating. Thus, the use of HSC as HSS-filling is in particular interesting for massive columns since its thermal properties do not play crucial role as in the case of leaner columns. This results in remarkably enhanced fire resistance. Yet this advantage diminishes with rising A/V-ratios. For the given load level, the application of HSC might not be reasonable for ratios exceeding a value of 15. The parametric study is once more repeated using the Canadian material properties.

For a direct comparison between both approaches, the average of the computed fire resistance period for the tens columns according to the Canadian approach is divided by the analogous value calculated according to the European standard. The ratio for each concrete class is presented in Figure 4. It is apparent that the Canadian results become more conservative with rising concrete strength.
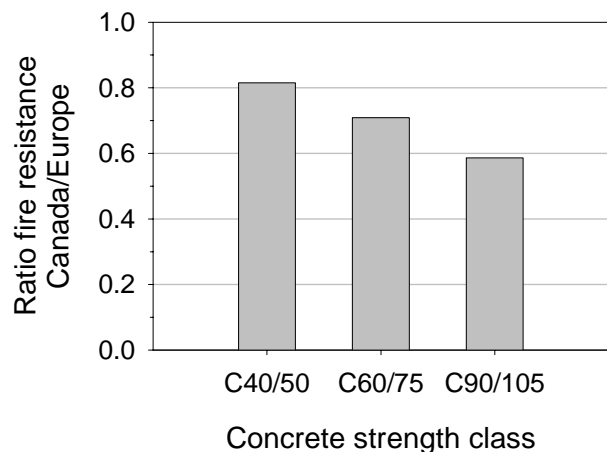

Figure 4. Comparison between European and Canadian material properties for varying A/V-ratios.

5 EFFECT OF CROSS-SECTION SHAPE

The fire resistance of a column is also influenced by the shape of the cross-section. To illustrate this effect, a numerical study is carried out. Consequently, three of the previous investigated circular HSS cross-sections are taken as the base of comparison. Since it was shown that the A/V-ratio has crucial influence on the fire endurance, the square HSS columns have the same A/V-ratio as the circular HSS columns. In addition, the wall thickness of the square HSS columns is calculated such that the resulting steel area for the square section is the same as for circular cross-section. This is necessary to account for the decreasing material properties of steel at elevated temperatures. The examined columns can be found in Table 1.

Table 1. Parameters for numerical study.

Cross-section		A/V-ratio	Load for C90/105	
		m⁻¹	kN	kN
Circular	Square		Circular	Square
CS1 C610 x 16	SQ610 x 12.5	7	15,316	20,628
CS2 C273 x 8	SQ273 x 6.2	15	3117	4214
CS3 C139.7 x 4	SQ139.7 x 3.1	29	813	1103

The HSS columns, which have a load level of 50% at room temperature, are filled with calcareous C90/105 concrete. The first value denotes the compressive strength of the concrete in MPa based on cylinder strength, whereas the second value is based on cube strength. Second-order effects are excluded with a chosen column length of only 0.50 m (short columns) with fixed-fixed end conditions.

The fire endurance for the different HSS steel columns with HSC-filling is presented in Figure 5. It is apparent that the circular cross-sections show a slightly better fire resistance period than the square cross-sections with the same A/V-ratio. Whereas the difference between the massive C610 x 16 mm and SQ610 x 12.5 mm cross-sections is only 6% (CS1), it amounts to about 11% for two other examples (CS2 and CS3).
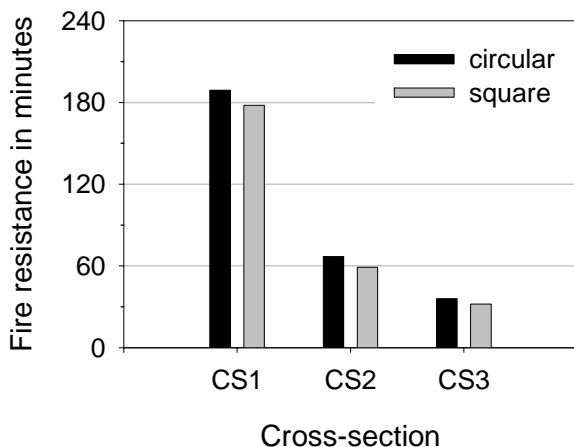

Figure 5. Comparison between circular and square cross-sections with same A/V-ratio.

The lower fire resistance in square columns can be explained based on the fact that in square cross-section corners are heated from two sides which leads to an increased supply of heat and thus earlier failure. This is illustrated in Figure 6. In the case of square columns, the temperature at a given distance from the edge is higher at the corner than that along the sides caused by the heat transfer from two sides.

In contrast to this, the circular cross-section shows a uniform temperature distribution along the radial lines. However, the investigation illustrates that the difference between the two cross-sections is moderate. Therefore only circular cross-sections are considered in the remaining case-studies. Considering that square cross-sections show lower fire endurance of about 10%, the numerical results for the circular HSS columns in general allow fire resistance assessment of square cross-sections with comparable A/V-ratio.
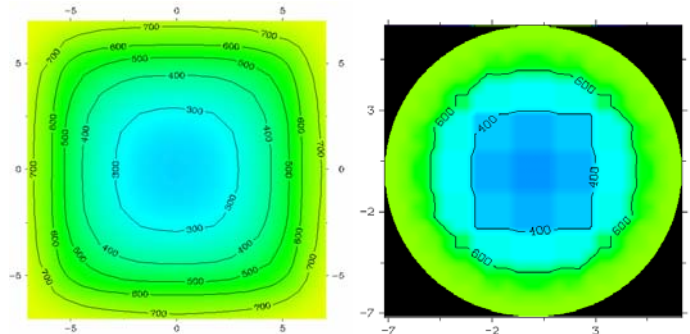

Figure 6. Temperature field for square SQ139.7 x 3.1 mm and circular cross-section C139.7 x 4 mm (CS3) after 32 minutes.

6 EFFECT OF SLENDERNESS

Columns are primarily compression members, however they are susceptible to bending with respect to column slenderness and load eccentricity. Thus, a numerical study was carried out to set a reasonable limitation for the use of HSC as HSS-filling.

The parametric study was carried out with a circular cross-section C219.1 x 6 mm and with hinged end conditions. A HSS column was filled with calcareous aggregate concrete with a compressive strength of 40, 60, 80 or 100 MPa based on cylinder strength. This corresponds to compressive strength of 50, 75, 95 and 115 MPa based on cube strength.

With regard to the tube, conventional yield strength of 235 MPa and improved yield strength of 355 MPa are chosen for the first two cross-sections. The third cross-section consists of a tube with yield strength of 235 MPa and additional 4 x 25 mm reinforcement bars.

The influence of slenderness is examined by varying the column length from 0.1 to 6 m with an assumed imperfection of L / 1000. Both the Canadian and European material properties for HSC are

used. The cross-sections are heated 30 minutes according to the ISO time-temperature curve. This standard curve according to the European code Eurocode 1, part 1-2 (prEN 1991-1-2) is very similar to the Canadian standard time-temperature curve, which is defined by the code ULC-S101. The short heating period of 30 minutes already shows the unfavorable fire endurance of slender HSC-filled HSS columns. For longer fire exposure times, the decline of ultimate load would be even more rapid.

After the heating process, the load is gradually increased until failure occurs.

6.1 Calculation with tube yield strength of 235 MPa

Results from the analysis are plotted in Figure 7, which shows the ultimate load-bearing capacity at 30 minutes as a function of column length. As expected, load carrying capacity decreases with increased length of the column. The Canadian code provisions are more conservative for both NSC and HSC under centric load, which is also illustrated in Figure 7. This is in particular true for the HSC class C100/115 as the European results for non-slender columns exceed the Canadian predictions about 25%.

Nevertheless, the differences between the approaches become less important for column lengths exceeding 2 m where buckling failure is crucial. In view of the fact that the stress-strain relationships compute very comparable results, the elastic modulus is very similar, too. This means in conclusion that no great differences with respect to buckling can be expected.
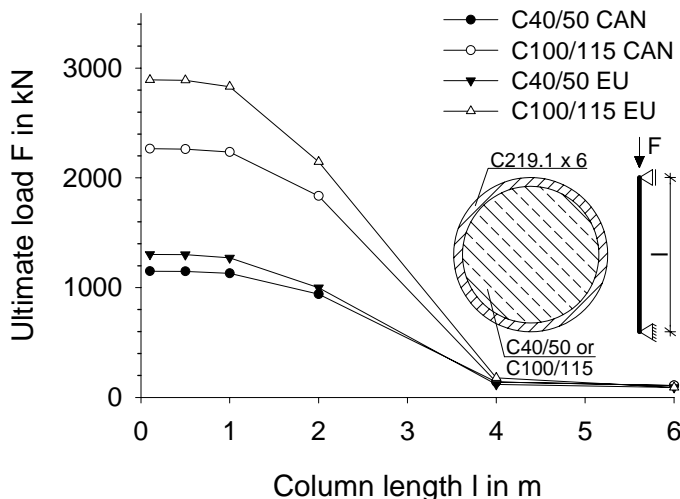

Figure 7. Ultimate load for HSC-filled HSS column with tube yield strength of 235 MPa under centric load using Canadian (CAN) and European (EU) material properties at 30 minutes fire exposure.

The results for moderate eccentric loads with e/h = 0.25 are given in Figure 8. The Canadian code provisions still calculate the more conservative results. Nevertheless, the difference between the ap-

proaches is insignificant for column lengths exceeding 2 m.

Due to its low tensile strength, the beneficial effect of concrete with high compressive strength is sharply reduced for slender columns and load eccentricities causing bending moments. Thus, the use of HSC as filling for HSS columns should be limited to non-slender columns with only moderate load eccentricity.
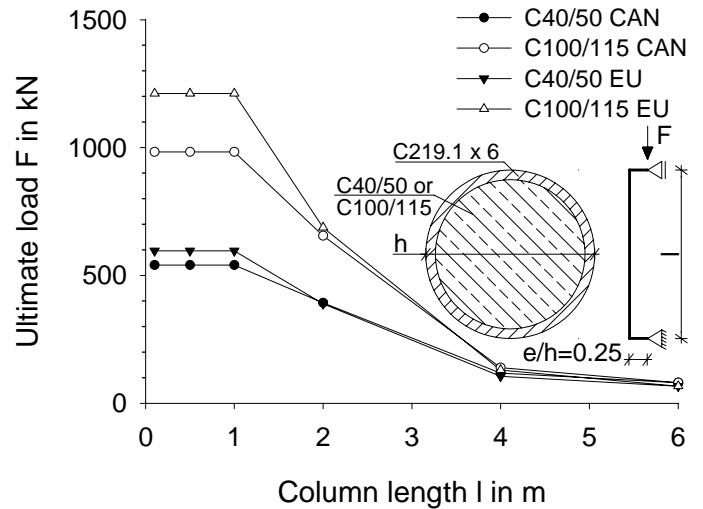

Figure 8. Ultimate load for HSC-filled HSS column with tube yield strength of 235 MPa and eccentric load of e/h = 0.25 using Canadian (CAN) and European (EU) material properties at 30 minutes fire exposure.

6.2 Calculation with tube yield strength of 355 MPa

The average steel temperature of the tube is 860°C for a fire exposure of 30 minutes. Thus, the load share of the steel tube is insignificant since its strength and elastic modulus are considerably reduced. The outcome is that the HSS column with the improved tube yield strength of 355 MPa carries only slightly greater loads than the cross-section with a steel tube having yield strength of only 235 MPa. Therefore the results are not presented in detail.

6.3 Calculation with tube yield strength of 235 MPa and reinforcement bars

The addition of reinforcement bars in concrete filling is helpful in improving fire resistance. This can be seen in Figure 9, where the HSS column with the tube of improved yield strength of 355 MPa is compared to the tube with yield strength of 235 MPa and additional 4 x 25 mm reinforcement bars.

With a concrete cover of 50 mm, the reinforcement bars are to some degree protected against heating. The outcome is an average temperature of 500°C in reinforcement bars remarkably reducing the elastic modulus to about 60% of its initial value according to the European code EN 1994-1-2. Nevertheless, in comparison to the directly fire-exposed

steel tube with an average temperature of about 860°C and corresponding reduction to only 8% of the initial elastic modulus, the beneficial effect of the column concrete cover is evident. Thus, the cross-section with additional bars shows superior behavior for slender columns since the elastic modulus is crucial for the buckling failure.

While the reasonable use of cross-sections with the improved tube is restricted to about 3 m for the examined column, cross-sections with reinforcement bars are able to bear a comparable amount of load up to a column length of approximately 6 m. In addition, the reinforcement bars allow the HSC to develop its beneficial effect on the load-bearing behavior since the difference between the concrete strength classes are more pronounced than for the cross-section with improved tube yield strength of 355 MPa.
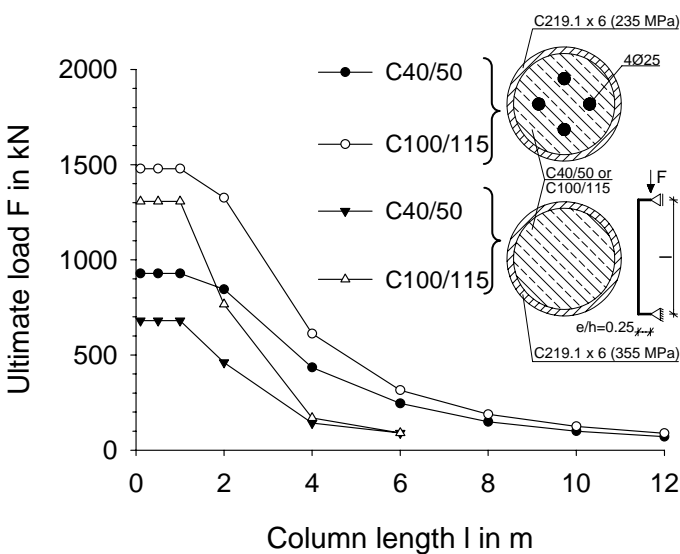

Figure 9. Comparison of ultimate loads between HSS column with tube yield strength of 235 MPa and additional reinforcement bars and tube of improved yield strength of 355 MPa both under eccentric load of e/h = 0.25.

7 CONCLUSIONS

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

- HSC-filling is particularly beneficial for massive columns with low A/V-ratio as the material properties of HSC at elevated temperatures do not play crucial role as in the case of leaner columns.
- Circular concrete-filled HSS steel columns provide higher fire resistance than square concrete-filled HSS columns of similar area of cross-section.
- The use of HSC as HSS-filling is reasonable for non-slender columns with only moderate load eccentricity. This recommendation is result of investigation on fire exposure of 30 minutes. Since the disadvantageous load-bearing behavior of HSC-filling increases with rising temperatures,

the conclusion is also valid for higher fire resistance classes.

- The fire resistance can be significantly enhanced by arranging reinforcement bars into the cross-section. The use of tubes with higher yield strength has very limited effect on the fire performance.

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