Guidelines for Fire Resistant Design of Concrete-Filled Steel HSS Columns - State-of-the-Art and Research Needs

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Abstract

The use of concrete filling offers a practical alternative for providing the required fire resistance in steel hollow structural section (HSS) columns and any amount of fire resistance in the practical range can be obtained through proper design. This paper presents a critical review on the fire performance of concrete-filled HSS columns. The various studies on fire resistance of concrete-filled steel columns are reviewed and the available design information for evaluating the fire performance of concrete-filled HSS columns is summarized. Practical guidelines that can be implemented during the design and construction phase, and which have beneficial effects on the fire-resistance behaviour of concrete-filled hollow steel columns, are presented. The applicability of the current design and construction guidelines in field applications is examined, and the various limitations of the current design approaches are discussed. Finally, steps needed for the development of an approach for performance-based fire safety design for concrete-filled steel columns is outlined.

Keywords: fire resistance, HSS columns, concrete-filled, design equation, performance-based design

1. Introduction

Steel hollow structural section (HSS) columns are very efficient in resisting compressive loads and are used in the construction of framed structures in office and industrial buildings. Structural fire safety is one of the primary considerations in the design of high-rise buildings and hence, building codes normally require fire protection for these HSS columns. Providing such external fire protection to HSS columns involves additional cost, reduces aesthetics of the building, and decreases usable space in a building.

Often these HSS 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. In addition, a higher fire resistance can be obtained without using external fire protection for the steel, thus increasing the usable space in the building and removing the need for maintenance of the fire protection. Further, the steel sections dispose with the need for form work and can be prefabricated, thus enabling their erection in all types of weather. 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; Twilt et al., 1996). These advantages have led to the increased use of concrete-filled HSS columns in recent years.

In the last two decades, a series of research studies have been undertaken and simplified calculation methods for evaluating the fire resistance of HSS columns filled with different types of concrete have been developed. Both experimental and numerical studies on the fire resistance of HSS columns filled with plain concrete, bar-reinforced concrete, and steel fiber-reinforced concrete were carried out (Kodur and Lie, 1995; Kodur and MacKinnon, 2000). These studies resulted in practical solutions for obtaining the required fire resistance for HSS columns, without any external protection, through concrete-filling.

Design guidelines for achieving fire resistance ratings through concrete filling have been incorporated into codes and standards. However, the current fire guidelines are limited in scope and restrictive in application since they were developed based on ASTM E-119 (2001) standard fire tests and are valid only for a narrow range of column dimensions and loads. In many applications, such as atriums, schools, and airports, where exposed steel is highly desired, the length and size of columns are beyond those allowed in the current design equations and thus, the designers can not take advantage of the high fire resistance obtained through concrete filling.
resistance ratings that can be achieved from concrete-filled steel columns.

This paper presents a critical review on achieving fire resistance in HSS columns through concrete-filling. The various fire resistance studies on concrete-filled steel columns are reviewed and the available design equations for evaluating the fire resistance of concrete-filled HSS columns are summarized. Practical guidelines that can be implemented during the design and construction phase, and which have beneficial effects on the fire-resistance behaviour of concrete-filled HSS columns, are presented. The various limitations in the current approaches are discussed. Research needed for the development of a performance-based approach for fire safety design of concrete-filled steel columns is outlined.

2. HSS Columns and Fire Safety

Steel hollow structural sections are gaining popularity due to the number of advantages they offer over other shapes. When used in buildings, these columns have to satisfy fire resistance requirements prescribed in building codes. This is because fire represents one of the most severe environmental conditions to which structures may be subjected, and hence, the provision of appropriate fire safety measures for structural members is an important aspect in the design of high-rise buildings. The required fire resistance ratings, as per building codes, can be anywhere in the range of 1 to 4 hours and depends on a number of factors such as type of occupancy, height of the building and building location. HSS sections, on their own, have fire resistance of about 20 to 25 minutes and hence have to be provided with some kind of fire protection, to achieve required fire resistance ratings (Kodur, 1999; Lie and Kodur, 1996).

Fire resistance of HSS columns is generally achieved by providing external fire proofing to steel. The external fire proofing is generally through the use of intumescent paints or through the application of an insulation material, such as spray on fire proofing or gypsum board. Such fire proofing measures, which are highly prescriptive in nature, add to the cost of the structure and also do not permit the possibility of exposed steel. Also, durability (adhesion and cohesion to steel) of fire proofing is often an uncertainty issue, and hence requires periodic inspection and regular maintenance, which in turn incurs additional costs during the life time of the structure (FEMA, 2002; NIST, 2005).

The second option available for achieving required fire resistance is through the use of “Fire-Trol column” (Fire-Trol, 2006). The “Fire-Trol column”, shown in Fig. 1, is a prefabricated, fireproofed unit consisting of a load-bearing steel column (A), encased in a special proprietary insulating material (B), which is permanently protected by an outer nonload-bearing steel shell (C). Fire-Trol columns are rated (prescriptive requirements) and labeled by Underwriters’ Laboratories, Inc., for fire retardant classifications of 2, 3, and 4 hours. Columns are completely shop fabricated and shipped to the job site ready to erect. There are a number of disadvantages with this system, which include additional costs of fire protection, reduced available space in the building, prescriptive based solutions for fire ratings and added transportation costs. As an illustration, the insulating material provided in these columns can consume significant space (see Fig. 1), which often can be two times the size of the steel section.

Alternate approaches for achieving fire resistance of steel HSS columns has been studied for some time to determine how the fire resistance can be enhanced without external fire protection (protective coatings). Methods such as filling the HSS columns with liquid (water) and concrete are the most popular approaches studied by researchers (Bond, 1975; Kodur and Lie, 1995; Klingsch and Wittbecker, 1988). However, the use of concrete-filling was the most attractive and feasible proposition developed by researchers.

Alternate approaches for achieving fire resistance of steel HSS columns has been studied for some time to determine how the fire resistance can be enhanced without external fire protection (protective coatings). 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. Eliminating such external fire protection increases usable space in the building and also leads to realizing exposed steel, which enhances the architectural beauty of the structure.

The use of concrete filling in HSS columns is increasing due to overcoming of many of the constructability issues, such as “connections” and “concrete filling methods” (Packer and Henderson, 1997; AISC, 1998; Kodur and MacKinnon, 2000). As a result, in recent years, a number of tall buildings have been built with concrete-filled steel

3. Fire Performance of Concrete Filled HSS Columns

This approach of using concrete filling to achieve fire safety was developed primarily in Europe and North America in the last two decades. Both experimental and theoretical studies, using numerical techniques, were carried out to investigate the influence of three types of concrete-filling; namely, plain concrete (PC), bar-reinforced concrete (RC), and steel fibre-reinforced concrete (FC), on the fire resistance of HSS columns (Kodur and MacKinnon, 2000; Grandjean et al., 1981; Kodur and Lie, 1995; Kodur and Lie, 1996; Kodur, 1997). These studies led to the development of innovative practical solutions for obtaining required fire resistance for HSS columns, without any external protection, through concrete-filling.

3.1. Fire resistance tests

The fire resistance test on concrete-filled HSS columns were predominantly carried out at National Research Council of Canada (NRCC) and a few organizations in Europe and Asia. The experimental program at NRCC consisted of fire tests on about 80 full-scale concrete-filled HSS columns (Kodur and Lie, 1995; Kodur and Lie, 1995; Lie and Chabot, 1992). Both square and circular HSS columns were tested and the influence of various factors, including type of concrete filling (PC, RC, and FC), concrete strength, type and intensity of loading, and column dimensions were investigated. During a 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 standard temperature-time curve (ASTM, 2001). The furnace, concrete and steel temperatures, as well as the axial deformations and rotations, were recorded until failure of the column occurred. The tests reported by other European studies (Grandjean et al., 1981; Finnish, 1989; Klingensch and Wittberger, 1988) are similar to NRCC tests, but instead use the ISO 834 (1975) standard fire; whose time-temperature curve is similar to that of ASTM E119 (2001).

Data reported from fire tests can be used to illustrate the behaviour of concrete-filled HSS columns under fire conditions. Figure 2 shows the variation of the axial deformation as a function of time for a typical HSS column filled with three types of concrete, namely plain concrete (PC), steel fibre reinforced concrete (FC), and reinforced concrete (RC) (Kodur and Lie, 1995). The three columns had similar dimensions and loading conditions and the results can be used to illustrate the comparative fire behaviour of the three types of concrete filling. At room temperature, the load is carried by both the concrete and the steel. When the column is exposed to fire, however, the steel carries most of the load during the early stages because the steel section expands more rapidly than the concrete core. At higher temperatures, the steel section gradually yields as its strength decreases, and the column rapidly contracts at some point between 20 and 30 minutes after exposure to fire. At this stage, the concrete-filling starts carrying more and more of the load. The strength of the concrete decreases with time and ultimately, when the column can no longer support the load, failure occurs either through buckling or compression. The elapsed time that it takes for the column to fail is the measure of its fire resistance. The behavior of the column, after steel yields, is dependent on the type of concrete-filling. The concrete core significantly contributes to an increased fire resistance of concrete filled HSS columns. This contribution comes from the higher heat capacity of concrete and longer retention of concrete strength with temperature.

It can be seen in Fig. 2 that the deformation behaviour of the FC-filled steel column is similar, during the later stages of the test, to that of the RC-filled steel column. The initial higher deformations in the FC-filled HSS column might be due to higher thermal expansion of steel fibre-reinforced concrete. The fire resistance of RC-filled HSS columns is higher than that of FC-filled HSS columns, which in turn is higher than PC-filled HSS columns.

A review of the results of fire resistance experiments shows that filling the column with plain concrete, without any steel reinforcement, offers the most economical arrangement from the point of view of fire resistance. However, in some cases, especially when the dimensions of the columns are large (323 mm or more), PC-filled steel columns fail at relatively low loads when exposed to fire. These failures can be attributed to early cracking initiated by strength loss in the steel casing at elevated temperatures and excessive local stresses in the concrete due to the reduction in compressive strength of the concrete at elevated temperatures (Kodur and Lie, 1996; 1997).

In the bar-reinforced concrete-filled HSS columns, 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 (Lie and Kodur, 1996). The fire resistances of these columns was improved significantly. However, there is the additional cost of steel, and installation of the rebars in the HSS column.

The use of fibre-reinforced concrete-filling in HSS columns provides better fire behaviour and resulted in fire resistance values which are comparable to those of RC-filled HSS columns (Kodur, 1997). The load-carrying capacity of the column is also increased to a certain degree. This can be attributed to the fact that the compressive strength of fibre-reinforced concrete increases with temperature up to about 400°C. The additional cost in the
case of FC-filled columns, over the cost of concrete, is the cost of the steel fibres.

3.2. Numerical studies

The numerical studies, primarily carried out by NRCC, consisted of development of mathematical models for predicting the behavior of circular and rectangular HSS columns filled with concrete and exposed to fire (Lie and Chabot, 1990; Kodur and Lie, 1996; 1997). In these models, the fire resistance is evaluated in various time steps, consisting of the calculation of the temperature of the fire, to which the column is exposed, the temperatures in the column, its deformations and strength during exposure to fire and, finally, its fire resistance.

At each time step, the fire temperature is estimated using the ASTM E119 (2001) standard fire time-temperature equation. A finite difference technique is used to compute the temperatures across the cross section of the column. The strength of the column, which decreases with duration of exposure, is computed using a stability analysis.

The strength reduces gradually with fire exposure time and eventually reaches a point at which the strength becomes so low that the column can no longer support the load. At this point, the column becomes unstable and is assumed to have failed either by buckling or by compression. In PC and FC-filled steel columns the compression failure was through crushing of concrete while in RC-filled steel columns the yielding of reinforcement also occurred. The time required from the initial fire exposure to reach the point at which a column becomes unstable, leading to failure under a given load, is taken as the fire resistance.

The above numerical procedure was incorporated into computer programs. These programs were used to generate extensive data on the behavior of concrete-filled steel columns under fire conditions. By specifying the mechanical and thermal properties of structural steel (HSS), reinforcing steel and concrete, at elevated temperatures, the fire resistance of circular or rectangular HSS columns filled with concrete was evaluated. The validity of the computer programs has been established by comparing the results of the model to test data. Full details on the development and validation of these models are given in References (Lie and Chabot, 1990; Kodur and Lie, 1996; 1997).

The computer programs can be used to generate alternate fire resistance solutions for a given concrete-filled steel column. Figure 3 illustrates the alternate fire resistance solutions that were generated for the three columns using the computer programs. It can be seen that the fire resistance varies from about 60 minutes to more than three hours depending on the size of the column and the type of concrete filling. This is in comparison to an unprotected un-filled HSS column, which has a fire resistance of about 20 minutes.

From the reported parametric studies (Lie and Stringer, 1994; Kodur and Lie, 1996; Kodur, 1997), the most important parameters that influence the fire resistance of concrete-filled HSS columns are:

- Type of concrete filling (plain, bar-reinforced, and fibre-reinforced)
- Outside diameter or the outside width of the column
- Load on the column
- Effective length of the column
- Concrete strength
- Type of aggregate
- Eccentricity of load

The analysis of data from detailed experimental studies has shown that the wall thickness of the HSS does not play a significant role in column fire resistance.

3.3. Design equation for evaluating fire resistance

Using the results from computer-simulated parametric studies, as well as fire resistance tests, a unified design equation has been developed for calculating the fire resistance of circular and square HSS columns filled with any of the three types of concrete (Lie and Stringer, 1994; Kodur, 1999; Kodur and MacKinnon, 2004). The equation expresses the fire resistance of concrete-filled HSS column, as a function of influencing parameters:
Tubulaire (Lie and Kodur, 1996; Kodur, 1997; Twilt pour le Développement et l’Étude de la Construction fire tests conducted by NRCC and by Comité International computer program developed at NRCC, as well as with predictions from Eq. (1) with those obtained from the parameter $f$ are shown in Table 1.

Values of the thickness of concrete cover, and the cross-sectional (carbonate or siliceous), the percentage of reinforcement, filling (PC, RC, and FC), the type of aggregate used HSS columns, filled with plain, bar-reinforced, or steel fibre-reinforced concrete. However, the equation is valid for limited range of variables specified in Table 2.

The above equation has been validated by comparing the predictions from Eq. (1) with those obtained from the computer program developed at NRCC and by Comité International pour le Développement et l'Étude de la Construction Tubulaire (Lie and Kodur, 1996; Kodur, 1997; Twilt et al., 1996). The fire resistances obtained using the equation are somewhat more conservative (about 10-15%) than those obtained from the tests, particularly for the range of higher fire resistances.

Equation (1) is applicable to both circular and square HSS columns, filled with plain, bar-reinforced, or steel fibre-reinforced concrete. However, the equation is valid for limited range of variables specified in Table 2.

The above design formula, which is based on the results of a large number of computer runs, and verified using the results of full-scale tests, enable the calculation of the fire resistance of concrete-filled HSS columns for standard fire exposure. Further, the formula calculates the fire resistance of columns as a function of parameters such as section dimensions, load and material properties. Using such formulas, engineers can design the most economical structural member, based on rational design principles, to obtain the required fire resistance, simply by varying the parameters. Also, the fire resistance design can conveniently be integrated with structural design since the fire resistance is expressed in terms of structural design parameters.

### 4. Guidelines for Fire Resistance Design

The above research studies clearly demonstrated that concrete-filling in HSS sections offers attractive proposition for achieving required fire resistances in the practical range. While fire resistance up to 2 hours can be achieved with plain concrete filling, fire resistance of 3 hours or more can be achieved with bar-reinforced concrete-filling or steel fibre-reinforced concrete-filling.

A review of various codes, standards and other research publications indicate that guidance is available for fire resistance design of concrete-filled columns. The fire resistance equations described above have been incorporated into the National Building Code of Canada (2005) and other standards such as ASCE-29 (1999), ACI 216 (1997) and AISC Fire Guide (Ruddy et al., 2003). The fire resistance guidelines for concrete-filled HSS columns specified in Europe (Finnish, 1989; Twilt, 1988; Twilt et al., 1996), Australia and New Zealand are very much similar to the ones above. The following are some broad guidelines which, when implemented during the design and construction phases, helps in achieving better fire performance.

#### 4.1. Design guidelines

The use of concrete filling offers a practical alternative for providing the required fire resistance in HSS columns. Any amount of fire resistance in the practical range can be obtained by properly designing the concrete-filled steel columns.

In general, HSS columns filled with either bar-reinforced or steel fibre-reinforced concrete should be used whenever a fire resistance greater than two hours is required. For slender columns and for columns with eccentric loads, bar-reinforced concrete or fibre-reinforced concrete should be used because the behavior of plain concrete-filled columns is unpredictable under these conditions.

For very high axial compression, only bar-reinforced concrete filling should be considered, as plain concrete-filled columns will usually be inadequate. This can be verified with the restrictions for axial load levels specified in Table 2.

The use of carbonate aggregate in concrete-filling provides about 10% higher fire resistance than siliceous aggregate.

### Table 1. Values of parameter $f$ in equation (1) for circular and square HSS columns (Kodur, 1999)

<table>
<thead>
<tr>
<th>Filling type</th>
<th>Plain concrete (PC)</th>
<th>Bar-reinforced concrete (RC)</th>
<th>Fiber-reinforced concrete (FC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate type</td>
<td>$S^1$</td>
<td>$C^2$</td>
<td>$S^1$</td>
</tr>
<tr>
<td>% of steel reinforcement</td>
<td>N/A</td>
<td>&lt;3%</td>
<td>N/A</td>
</tr>
<tr>
<td>Thickness of concrete cover</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
</tr>
<tr>
<td>Circular HSS</td>
<td>0.07</td>
<td>0.08</td>
<td>0.075</td>
</tr>
<tr>
<td>Square HSS</td>
<td>0.06</td>
<td>0.07</td>
<td>0.065</td>
</tr>
</tbody>
</table>

$^1$Siliceous, $^2$Carbonate, $^3$% of steel fibers by mass.

![Equation](image)

where:

- $R$ = fire resistance in minutes
- $f_0^*$ = specified 28-day concrete strength in MPa
- $D$ = outside diameter or width of the column in mm
- $C$ = applied load in kN
- $K$ = effective length factor
- $L$ = unsupported length of the column in mm
- $f$ = a parameter to account for the type of concrete filling (PC, RC, and FC), the type of aggregate used (carbonate or siliceous), the percentage of reinforcement, the thickness of concrete cover, and the cross-sectional shape of the HSS column (circular or square). Values of parameter $f$ are shown in Table 1.
A higher fire resistance is obtained with circular concrete-filled steel columns than with square concrete-filled steel columns having the same cross-sectional area.

### 4.2. Construction guidelines

The use of bar reinforcement is not recommended for HSS columns smaller than 200 mm due to practical difficulties in the installation of the rebars and in obtaining full consolidation of the concrete. In such cases FC-filling offers an attractive alternative to RC-filling.

For RC-filled columns the minimum concrete cover to reinforcement should be at least 20 mm. Stirrups must be provided over the full length of the column and the spacing of the stirrups should be same as those for the reinforced concrete columns.

The location of the reinforcing bars must be fixed by the use of stirrups and spacers. Stirrups need not be designed for shear forces because of the high shear force resistance of the hollow section in fire situations.

Concrete filling of HSS columns can be accomplished in situ by gravity. The concrete should be vibrated. Special care should be taken to ensure that there are no voids in the columns.

Small drain holes, with minimum diameter of 12.7 mm, must be provided in the walls of the HSS in pairs at each floor level. These holes are intended to prevent the bursting of the column under steam pressure generated by the heating of entrapped water in the enclosed concrete.

### 4.3. Field applications

The fire design equation and solutions, discussed above, were instrumental in developing and visualizing exposed steel (HSS columns) in a number of buildings including the Museum of Flight building in Seattle, WA, and school buildings in Hamilton, Canada (Kodur and MacKinnon, 2000). The calculation methods were successfully applied to develop required fire resistance for steel HSS columns through concrete-filling. Figure 4 shows an elevation of exposed steel column, in a Hamilton School Building, where a 1 hour fire resistance was achieved through plain concrete-filling (Kodur and Lie, 1995).

### 5. Limitations of Current Design Approach

The above developed equation and associated fire guidelines, though providing an innovative and cost-effective approach to visualize exposed steel, are limited in scope and restrictive in application since they were developed based on ASTM E-119 (2001) standard fire tests and are valid only for narrow range of column dimensions, loads and other design variables. The following table (Table 3) gives some of the limitations of the approach developed above, and the range of variables encountered in field applications:

Thus, the current fire resistance provisions in codes and standards are highly prescriptive, very restrictive and too
mathematical model and simplified to a form that they is the use of design formulas, which are derived using the are subjected during exposure to fire. The other approach models that simulate the conditions structural members can be used. The first approach is the use of mathematical performance of structural members, two levels of analysis for evaluating fire resistance performancedesign is the fire resistant design of (Meacham and Custer, 1995; Kodur, 1999). For fire safety traditional prescriptive based approaches (AISC, 2005; moving towards performancedesign from the above research for ASTM E-119 (2001) fire exposure only. Therefore, the available design equations and solutions cannot be used under the recently introduced performance-based codes, which provide rational, cost-effective and innovative fire safety solutions.

In many applications, such as atriums, schools, and airports where exposed steel is highly desired, the length and size of columns are beyond those allowed in the current design equations and thus, the architects and designers can not take advantage of high fire resistance ratings (and other advantages) that can be achieved from concrete-filled steel columns. Also, the limitations of the above research for ASTM E-119 (2001) fire exposure only, is hindering the use of HSS columns in offshore structures and oil platform applications. Thus, the full potential for the use of these steel HSS columns has not been realized.

Due to above limitations in the current fire safety design methods, a number of opportunities for the use of steel HSS columns are being lost. Further, in places where concrete-filled HSS columns are used, external fire protection is still provided, without taking advantage of inherent fire resistance present in this composite system.

6. Future Trends and Research Needs

In recent years, there has been an increased focus in moving towards performancedesign from the traditional prescriptive based approaches (AISC, 2005; Meacham and Custer, 1995; Kodur, 1999). For fire safety design, the performancedesign approach is becoming popular due to the cost-effective and rational fire safety solutions they provide. One of the key aspects in any performancedesign is the fire resistant design of structural members. For evaluating fire resistance performance of structural members, two levels of analysis can be used. The first approach is the use of mathematical models that simulate the conditions structural members are subjected during exposure to fire. The other approach is the use of design formulas, which are derived using the mathematical model and simplified to a form that they can be incorporated in building codes.

At present, there are no methods or tools that can be applied for performancedesign of concrete-filled steel columns. A comprehensive research program is needed for developing a performancedesign approach to facilitate performancedesign of concrete-filled HSS columns for any given length, size, load and fire scenarios. The research output from such a research program will effectively eliminate fire protection for HSS columns, through concrete filling, and thus provide a large potential for the architects to create innovative designs using exposed steel (Wang and Kodur, 2000).

The main steps involved in developing a performancedesign approach for performancedesign are:

a) identifying proper design (realistic) fire scenarios and realistic loading levels on HSS columns under consideration;

b) carrying out detailed thermal and structural analysis by exposing the concrete-filled HSS column to realistic fire conditions; and

c) developing relevant practical solutions, such as use of different types of concrete filling, to achieve required fire resistance.

The design fire scenarios for any given situation should be established either through the use of parametric fires (time-temperature curves) specified in Eurocodes or through actual calculations based on ventilation, fuel load and surface lining characteristics (EC 1, 1994; SFPE, 2004). Figure 5 shows typical standard and real fire exposure curves that can be used for performancedesign fire safety design. The load that are to be applied on concrete-filled HSS columns, in the event of fire, should be estimated based on the guidance given in ASCE-07 standard (ASCE-07, 2003) (dead load + 50% live load) or through actual calculation based on different load combinations.

Once the fire scenarios and load level are established, the next step is to employ a computer program for the analysis of concrete-filled steel columns exposed to fire scenarios. The computer program should be able to trace the response of the concrete-filled HSS column in the entire range of loading up to collapse under fire. Using the computer program, a coupled thermal-structural analysis shall be carried out at various time steps. In each

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Current limitation</th>
<th>Practical applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column shape</td>
<td>square and circular</td>
<td>square, circular and rectangular</td>
</tr>
<tr>
<td>Column size</td>
<td>400 mm</td>
<td>600 mm and beyond</td>
</tr>
<tr>
<td>Column length</td>
<td>4 m</td>
<td>15-20 m</td>
</tr>
<tr>
<td>Concrete strength</td>
<td>55 MPa</td>
<td>100 MPa</td>
</tr>
<tr>
<td>Fire scenarios</td>
<td>ASTM E-119</td>
<td>design fires and hydrocarbon fires</td>
</tr>
<tr>
<td>Load level</td>
<td>strength of concrete core</td>
<td>service loads</td>
</tr>
<tr>
<td>Eccentric loads</td>
<td>not allowed</td>
<td>always present</td>
</tr>
</tbody>
</table>
time step, the fire behavior of a concrete-filled HSS column is estimated using a complex, coupled heat transfer/strain equilibrium analysis, based on theoretical heat transfer and mechanics principles. The analysis shall be performed in three steps: namely, calculation of fire temperatures to which the column is exposed, calculation of temperatures in the column, and calculation of resulting deflections and strength, including an analysis of the stress and strain distribution.

The program, used in the analysis, should be capable of accounting for nonlinear high temperature material characteristics, complete structural (column) behavior, various fire scenarios, high temperature creep, different concrete types (concrete with and without steel fibers), and failure criteria. In the analysis, geometric nonlinearity which is an important factor for slender columns (that are used in many practical applications), shall be taken into consideration. Thus, the fire response of the column shall be traced in the entire range of behavior, from a linear elastic stage to the collapse stage under any given fire and loading scenarios. Through this coupled thermal-structural analysis, various critical output parameters, such as temperatures, stresses, strains, deflections and strengths, have to be generated at each time step.

The temperatures (in the concrete, and reinforcement), strength capacities and computed deflections of the column shall be used to evaluate failure of the column at each time step. At every time step the failure of the column shall be checked against a pre-determined set of failure criteria, which include thermal and structural considerations. The time increments continue until a certain point at which the thermal failure criterion has been reached or the strength (or deflection) reach their limiting state. At this point, the column becomes unstable and will be assumed to have failed. The time to reach this failure point is the fire resistance of the column.

Alternatively, simplified design formula can be developed for performance-based fire safety design. In this case, the computer model shall be used to analyze a series of concrete-filled steel columns exposed to design fire scenarios. The columns, taken from typical commercial and office buildings, will have broad range of design parameters, such as column dimensions, and will be analyzed under various fire scenarios. In the analysis, the slenderness effects and material and geometric nonlinearity will be accounted for, and realistic failure criterion (not critical temperature consideration alone) will be used to determine the failure. Data from these numerical simulations, together with that from fire resistance experiments, can be used to develop a simplified methodology (empirical design equations) for performance-based fire safety design of concrete filled steel HSS columns.

The development of a performance-based approach will effectively eliminate fire protection for HSS columns and result in an efficient and cost effective solution (through concrete filling) for achieving required fire resistance. This will offer a large potential for architects to create designs using exposed steel, which is much more economical and attractive than using conventional columns. Thus, the performance-based approach is expected to significantly enhance the use of HSS columns and increase the market share for steel in building, industrial and offshore applications.

7. Summary

Concrete filling offers an attractive practical solution for providing fire protection to hollow structural steel columns without any external protection. The required fire resistance can be obtained for HSS columns through the use of one of three types of concrete filling: plain concrete filling, reinforced concrete filling or fiber reinforced concrete filling.

Limited design and construction guidelines are available for evaluating fire resistance of concrete-filled steel columns under standard fire scenarios.

The current fire resistance guidelines are highly prescriptive, very restrictive in application and can not be used under performance-based codes.

There is a strong need for the development of a rational approach for performance-based fire safety design of concrete filled steel columns. The development of performance-based methods for the assessment of the fire resistance of concrete-filled steel columns will further contribute to improving the cost efficiency of these efficient composite systems.

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