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Fire Resistance of Concrete-Filled Steel Columns

by V.K.R. Kodur

Filling a hollow steel column with concrete increases the column's load-bearing capacity as well as its fire resistance. Concrete reinforced with steel fibres or bars both offer advantages over plain-concrete filling. This article discusses the fire-protection advantages and other benefits achieved with the various types of concrete filling, with emphasis on steel-fibre technology.

Steel hollow structural section (HSS) columns are very efficient in resisting compression loads and are widely used in the construction of framed structures in industrial buildings. Steel is vulnerable to fire, however, and in the past, building codes normally required fire protection for these columns. This effectively eliminated the potential for architects to create designs using exposed steel.

Research conducted over a ten-year period at NRC's Institute for Research in Construction (IRC) using a large test furnace has shown that filling steel columns with concrete will increase both their load-bearing capacity and their fire resistance. The need for external fire protection for the steel is eliminated allowing architects and engineers to expose the steel in their designs — without jeopardizing fire safety. Added benefits include an increase in usable floor space and a reduction in fire-protection costs.

The new Museum of Flight in Seattle, Washington, home to one of the most extensive aircraft collections in the world, owes its sense of transparency and openness, in part, to its use of concrete-filled steel columns. One of the design requirements for the museum was that the exhibits be visible from the outside and the sky from the inside. This was achieved by enclosing

Figure 1. *The Museum of Flight in Seattle, Washington uses a bar-reinforced concrete-filled steel-column structure to help achieve its sense of openness and transparency.*

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the building in glass and supporting it by an unobtrusive structure (see Figure 1). The architects, aware that the greater fire resistance of concrete-filled steel columns would make them an obvious choice to fulfill this structural requirement, used IRC test data and computer programs to demonstrate to code authorities in the Seattle area that the required minimum one-hour fire-resistance rating at full design loads could be obtained.

Demonstrated Advantages

In recent studies supported by the North American steel industry, IRC researchers tested and developed computer models for both square and circular HSS columns. They investigated the influence of significant factors such as type of filling (plain concrete, bar-reinforced and steel-fibre-reinforced concrete), concrete strength, type and intensity of loading, column dimensions and slenderness ratio.

These studies demonstrated that HSS columns filled with steel-fibre-reinforced concrete have greater fire resistance than those filled with plain concrete and that their use permits more cost-effective construction. Steel-fibre-reinforced filling offers the following advantages over plain-concrete filling:

- greater tensile strength added to the composite system,
- less cracking under service conditions, and
- greater resistance to deterioration from material fatigue, impact, shrinkage, and thermal stress.

Behaviour of Concrete-Filled HSS Columns in Fires

The performance of concrete-filled steel columns is unique. 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, either buckles or fails in compression. The time at which the column fails determines its fire-resistance rating.

Fire Performance of Different Types of Concrete Filling

Plain concrete

The fire resistance of columns filled with plain concrete is limited to between one and two hours. Failure occurs because of a reduction in the compressive strength of the concrete with increased temperature together with rapid crack propagation in the concrete, resulting in premature failure of the concrete core. Fire resistance of longer than one hour can be achieved by reducing the load levels. One cautionary note is that the fire resistance of these columns is very sensitive to eccentric loads, i.e., where loads act away from the longitudinal axis.

Steel-fibre-reinforced concrete

The fire resistance of steel columns can be improved significantly by filling them with steel-fibre-reinforced concrete instead of plain concrete (see Figure 2). Fire-resistance ratings of up to three hours can be obtained without any reduction in the load. The presence of steel fibres, about 2 percent by mass, reduces cracking in the concrete and contributes to the compressive strength at elevated temperatures, thus preventing premature failure of the concrete core.

These benefits can be attributed to the superior mechanical and thermal properties of steel-fibre-reinforced concrete at elevated temperatures, and to the containment effect provided by the steel fibres to the concrete core.

The increased cost of using steel-fibre-reinforced concrete rather than plain concrete as a filling for HSS columns can often be justified by the numerous advantages offered, including:

- better deformation behaviour, resulting in gradual rather than sudden failure (see Figure 2);
- increased load-carrying capacity — of between 10 and 20 percent;

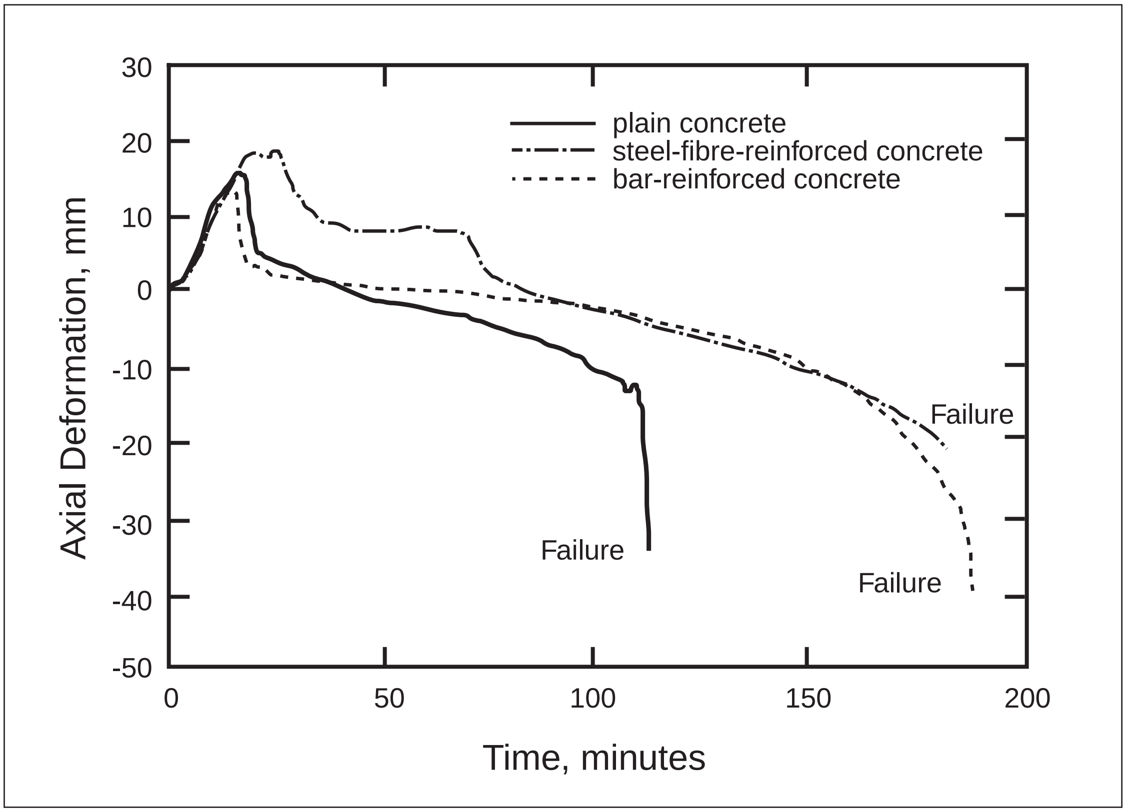

Figure 2. The figure shows the comparative fire-resistance capacity of a typical HSS column with three types of concrete filling. The variation in axial deformation with time when the column is subjected to fire demonstrates the superior deformation behaviour of steel-fibre-reinforced concrete (ductile, or gradual, failure) compared to that of plain concrete filling (brittle, or sudden, failure).

- increased fire resistance — of between 2 and 3 hours — even under eccentric loads;
- decreased buckling;
- suitability for a wide range of column dimensions.

Bar-Reinforced Concrete

Columns filled with bar-reinforced concrete offer many of the same advantages of columns filled with steel-fibre-reinforced concrete. They are, however, more expensive because of the labour involved in placing the reinforcing bars. They are also more difficult to work with in confined spaces with regard to achieving sufficient concrete coverage of the reinforcing bars.

Predicting Fire Resistance

Data generated from the IRC fire tests have been used not only to determine the influence of different parameters on the fire resistance of concrete-filled columns but also to validate computer programs that can predict the fire resistance of these columns.

In turn, data from these computer studies have been used to develop simple design equations that can be used to calculate the fire resistance of HSS columns filled with concrete.

The 1995 edition of the National Building Code (NBC), Appendix D, Section D-2.6.6., recognizes the fire resistance of steel HSS columns filled with plain concrete and includes design equations for calculating their fire resistance. Similar equations for columns filled with steel-fibre-reinforced concrete and with bar-reinforced concrete will likely be included in future editions of the NBC.

These equations can simplify the structural design process and thus encourage the use of these types of concrete filling. By varying parameters such as load, column-section dimension or concrete strength, it is possible to achieve an optimum design that is not

Figure 3. *A recently built school in Hamilton, Ontario in which HSS columns filled with bar-reinforced concrete were used*

only economical but also based on rational design principles.

In the meantime, computer programs developed by IRC for predicting the fire resistance of concrete-filled columns can assist designers and regulators in evaluating the fire resistance of building elements in cases where no specific data exist. In addition to the Museum of Flight in Seattle, two recently built schools in Ontario (see Figure 3), in which HSS columns filled with bar-reinforced concrete were used, represent successful applications of IRC's computer programs.

Conclusions

The use of concrete filling in hollow steel columns is an effective way to increase the fire resistance of these columns and to reduce fire-protection costs, while giving architects the freedom to create pleasing designs using exposed steel. For many tall buildings, there will be no need to increase the diameter of the columns for lower floors because of the greater load-bearing capacity afforded by the concrete filling. Other benefits include increased usable floor space and reduced construction costs because this type of column can be prefabricated and erected in all types of weather.

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