Structural Design for Fire Conditions

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Practical applications of AISC 2010 *Specification* Appendix 4.

WHEN ARCHITECTS AND STRUCTURAL ENGINEERS develop innovative structural designs, they often encounter the limitations inherent to prescriptive structural fire resistance code requirements. Structural fire resistance typically is based on standardized furnace tests of members and subassemblies. Catalogs of previously-tested components are available (such as the UL *Fire Resistance Directory*), and it is possible to assemble a complete building from such components. However, modern buildings can often include innovative or complex structural solutions for which furnace test data is not available. This type of testing can be highly expensive and time consuming and may not reasonably capture the performance of the unique structural solution in real fire conditions.

Appendix 4 of the 2010 AISC *Specification for Structural Steel Buildings* provides engineers with methodologies for designing and evaluating structural assemblies for fire conditions. While determination of fire resistance through standardized testing is an option presented in Appendix 4, the option of using engineering analysis to evaluate the fire performance of steel structures is also provided. This article discusses three different projects carried out by Arup in which analysis methodologies supported by Appendix 4 were used. This type of approach can support the design of robust structural systems and the optimization of structural fire performance without compromising architectural and structural design vision, all while maintaining life safety.

Because the performance of the structure is quantified in fire conditions, any strengths (e.g., structural redundancies, secondary load paths, over-sizing, etc.) and/or weaknesses expected when the "cold" structural design is exposed to fire conditions can be identified and addressed. In this way, the fire protection strategy can be tailored to the specific building. In many cases, this can lead to optimization (reduction or elimination) of fire protective materials and significant cost savings when compared to standard testing of unique structural elements.

While these types of approaches can be used in most regulatory environments with varying approval demands, it is very important to maintain an open dialogue with building officials and the design team to achieve agreement on the approach. These methodologies also require specialized knowledge in the response of structures to fire conditions.

Kauffman Center for the Performing Arts

The new Kauffman Center for the Performing Arts in Kansas City, Mo., will provide state-of-the-art theater and performance experiences for up to 3,400 visitors at a time between its two large performance halls. The halls are linked by a grand main lobby enclosed by a signature cable-stayed curved glass façade and a glass roof. Open stairs and galleries overlook the lobby and provide access to the theaters within.

The steel cable "nets" supporting the atrium façade and roof include exterior members that span above an adjacent roadway, which provides access to the main public entrance of the facility. Large buses are expected to use this road and to park near the lobby entrance, so there is a real possibility that the exterior steel cables could be exposed to a large

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Instead of cables, slightly larger hot-rolled steel tension rods (visible in the foreground) are providing fire safety at the Kauffman Center for the Performing Arts, under construction in Kansas City, Mo., without the need to apply additional protective material.

fire. These members are required by code to have a one-hour fire-resistance rating.

Fire protection of steel cables or rods under tension is challenging. It is sometimes not possible to adhere sprayed-on fire protective materials of the thickness required to achieve required fire resistance levels to small diameter cables or rods. Materials are available that can be cast into tube shapes and then applied to these members, but they add significantly to the diameter of the cable or rod. Both of these methods make the member look less like steel, which often is contrary to the design vision. Further, very limited test data is available regarding the fire performance of cables and rods under tension, so justification of a fire protection solution to the regulatory authorities can be a challenge.

Given the design team's desire to keep the exterior cables exposed and to avoid approvals risks and costly protective measures, Arup undertook an analysis of the inherent fire resistance of the steel cables. The fire performance of the cold-worked steel cables given a large bus fire on the roadway below was evaluated using a lumped heat capacity analysis, which is supported by Appendix 4 of the AISC *Specification* and discussed in the corresponding commentary section within that document. Through that analysis, it was determined that if the cables were replaced by hot-rolled steel tension rods and the diameter of the members was increased slightly, they would have sufficient inherent fire resistance to achieve the code-required fire resistance (under the loading conditions described in Appendix 4) and applied fireproofing would not be required. This solution is considered to be highly robust because the structure is intrinsically designed to withstand expected fires on its own rather than relying on applied protective materials that require continued maintenance. Also, this approach allowed the original design vision, with exposed steel members, to be realized.

Transbay Transit Center, San Francisco

The Transbay Transit Center will be a modern three-story, 70-ft-high, one million sq. ft regional transit hub located in downtown San Francisco. The above-grade portion of the building contains two levels of assembly/retail/office space, a bus deck level and a rooftop park of approximately 5.4 acres. The facility also will have two below-grade levels expected to serve Caltrain and the future California High Speed Rail network. According to the prescriptive requirements of the code, the structure is required to achieve a two-hour fire resistance.

The main lateral load resisting system of the building consists of a large, perimeter steel braced frame located external to the building envelope, which also projects away from the main structure. Because the steel frame is one of the key architectural features of the building, providing a traditional two-hour externally applied fire protection system (such as spray, gypsum board or intumescent paint) would reduce the aesthetic value of the exposed steel and might be cost prohibitive. In addition, due to the large diameter of the circular hollow sections (about 16 in.), justifying a fire protection solution using concrete filling to the regulatory authorities can be a challenge because fire test data generally incorporates significantly smaller sections.

Because the steel braced frame is designed primarily for high seismic demands, the members are over-sized for the fire limit state where the applied loads are significantly reduced. That means the elements have additional reserved capacity and may not require the code-prescribed level of applied fire protection to maintain the loads. Given that these elements are located along the building perimeter and external to the floor plate, the only credible design fire scenarios would be localized vehicle fires at street level, exposure to flames projecting out of the façade from a post-flashover retail/office compartment fire, or a localized bus fire at bus deck level. These fire scenarios are considered less severe than the standard two-hour fire exposure assumed by the code for design.

Arup undertook a performance-based structural fire engineering analysis to not only determine whether the prescribed two-hour fire resistance rating could be reduced and/or eliminated given realistic fire scenarios and the lesser loads in the fire limit state, but also to demonstrate robustness of the structure in severe fire conditions. The structural fire performance of the steel braced frame was evaluated using a range of analysis techniques supported by Appendix 4 of the AISC *Specification* (lumped heat capacity analysis and single element/whole frame thermal mechanical analysis) depending on the fire exposure and structural redundancy.

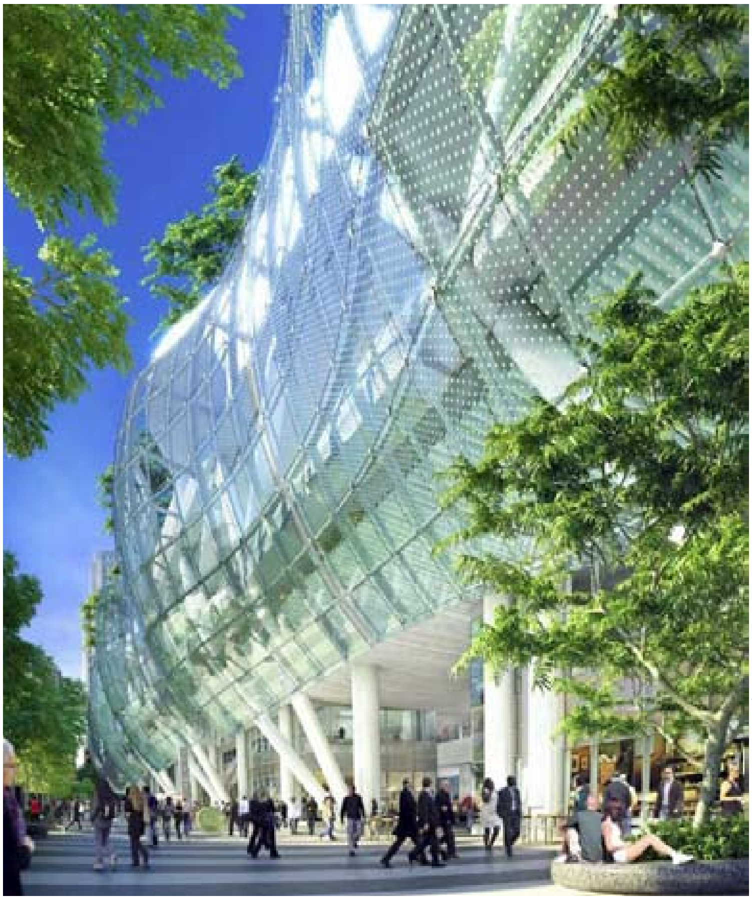
The advanced analysis demonstrated that the external braced frames at the bus deck level would be capable of maintaining stability during a fire event without applied fire protection. However, due to the expected fire severity and close proximity of portions of the external structure to possible interior fire locations at ground level, a fire protection solution was required for a portion of the lateral resisting system. To allow for the V-columns to be exposed, a secondary thermal-mechanical analysis was conducted to demonstrate that filling the large diameter hollow sections with concrete would provide an inherent two-hour fire resistance.

The performance-based solution not only satisfied the aesthetic aim of exposing the steel braced structure, but it also allowed the design team to identify the robustness of the structure under severe fire conditions and the corresponding high level of life safety provided.

Steel-Framed Parking Structure

Although parking structures in the U.S. often are constructed of concrete, it is increasingly common in other portions of the world to build such structures of steel, a practice which can bring numerous benefits in terms of both structural design and aesthetics. Arup recently had an opportunity to evaluate the fire resistance of such a structure for a proposed project.

The concept included a high-rise, mixed-use corporate campus with a five-story traditional steel-framed open parking garage located at levels 3-7. The parking levels of the campus constituted the largest area of any single level of the project, with a typical area of approximately 157,000 sq. ft per level. According to the relevant building code, the structural fire resistance ratings of the columns and primary/secondary beams in the parking garage were required to be three hours and two hours, respectively.



Using the approach permitted by Appendix 4 enabled engineers to demonstrate the Transbay Transit Center's inherent fire resistance and develop an aesthetically pleasing, performance-based solution without resorting to a traditional two-hour externally applied fire protection system.

Potential parking garage fires differ markedly from the typical building fires assumed by building codes for design. While building fires generally exhibit a steady growth phase and may grow to involve a large portion of the structure, parking garage fires tend to be localized fires that quickly reach a maximum heat release rate before burning out.

Recognizing the relatively low fire severity of parking garage fires compared to the multi-hour standard fire exposure assumed by the code, a performance-based structural fire analysis was conducted to assess the possibility of reducing and/or removing the code-prescribed level of fire resistance to the parking structure and to demonstrate the structure's robustness in fire conditions. As part of the advanced analysis, a range of credible design fire scenarios (involving one car, three cars, and five cars) was determined based on open parking garage fire statistics and test data. The thermal and spatial distribution of elevated temperatures was calculated for the range of fire scenarios to identify the extent of structure simultaneously exposed to high temperatures. Single-element thermal-mechanical analyses coupled with a whole-frame element removal analysis was conducted to quantify the response of the parking structure through the range of fire exposures.

Based on these analyses, Arup was able to demonstrate that the parking structure's secondary beams could be unprotected and the fire resistance requirements for the columns and primary beams could be reduced from three hours and two hours, respectively, to just one hour. We were able to show that with these reduced fire ratings the structure has sufficient capacity and structural redundancy to maintain stability in the fire limit state under a range of severe fire events, and thus would meet the life safety intent of the code.

The results of an analysis such as this cannot only demonstrate the robustness of structural systems under fire conditions, but also can reduce maintenance demands and enhance aesthetic value by allowing portions of the steel structure to be exposed. In this specific case, secondary beams could be left unprotected and columns and primary beams could be protected using aesthetically pleasing thin-film intumescent paint.

Summary

The case studies presented here demonstrate just some of the benefits that can be realized through application of the methodologies presented in Appendix 4 of the 2010 AISC *Specification*. Designing a structural system to take advantage of the inherent fire resistance of steel members under expected fire conditions can lead to better understanding of the actual level of life safety provided and to optimization of investment in fire protection strategies. MSC