Analytical investigation of vehicle fires in precast concrete parking structures

Stephen Pessiki and Jonathan Bayreuther

- A precast concrete parking structure was analyzed for a series of vehicle fires, and the resulting fire loads (temperature and heat flux time histories) at various locations in the structure were determined.
- Analyses were performed using a computational fluid dynamics computer program. Heat flux histories were used as input to finite element analyses to determine the temperature rise in the prestressing strand of the double-tee floor members. The increased prestressing steel temperatures were then used to estimate the reductions in steel strength.
- For the nine different fire scenarios considered, vehicle fires caused only minor reductions (maximum of 15%) in the strength of the prestressing steel of the double-tee floor members.

This paper describes part of a research program investigating the performance of structures in fire. The focus of this paper is the effect of vehicle fire loads in precast concrete parking structures. A prototype parking structure was analyzed for a series of vehicle fires, and the resulting fire loads (temperature and heat flux histories) at various locations in the structure were determined. Variables treated in the analyses include structure geometry and fire characteristics (single- versus multi-vehicle fires). Heat flux histories obtained from the fire analyses were used as input to finite element analyses to determine the temperature rise in the prestressing strand of the double-tee floor members. The increased prestressing steel temperatures were then used to estimate the reductions in steel strength. Bayreuther and Pessiki[1] provide complete details of the study presented in this paper.

Prototype structure

The parking garage on which the study is based is located on a sloping lot with three floors above grade on the south side and four on the north side. The floor height varies from 3.8 m (12 ft) on the ground floor to 3.1 m (10 ft) for each of the upper floors. Overall dimensions are approximately 69 m (227 ft) from east to west and 38 m (125 ft) north to south.

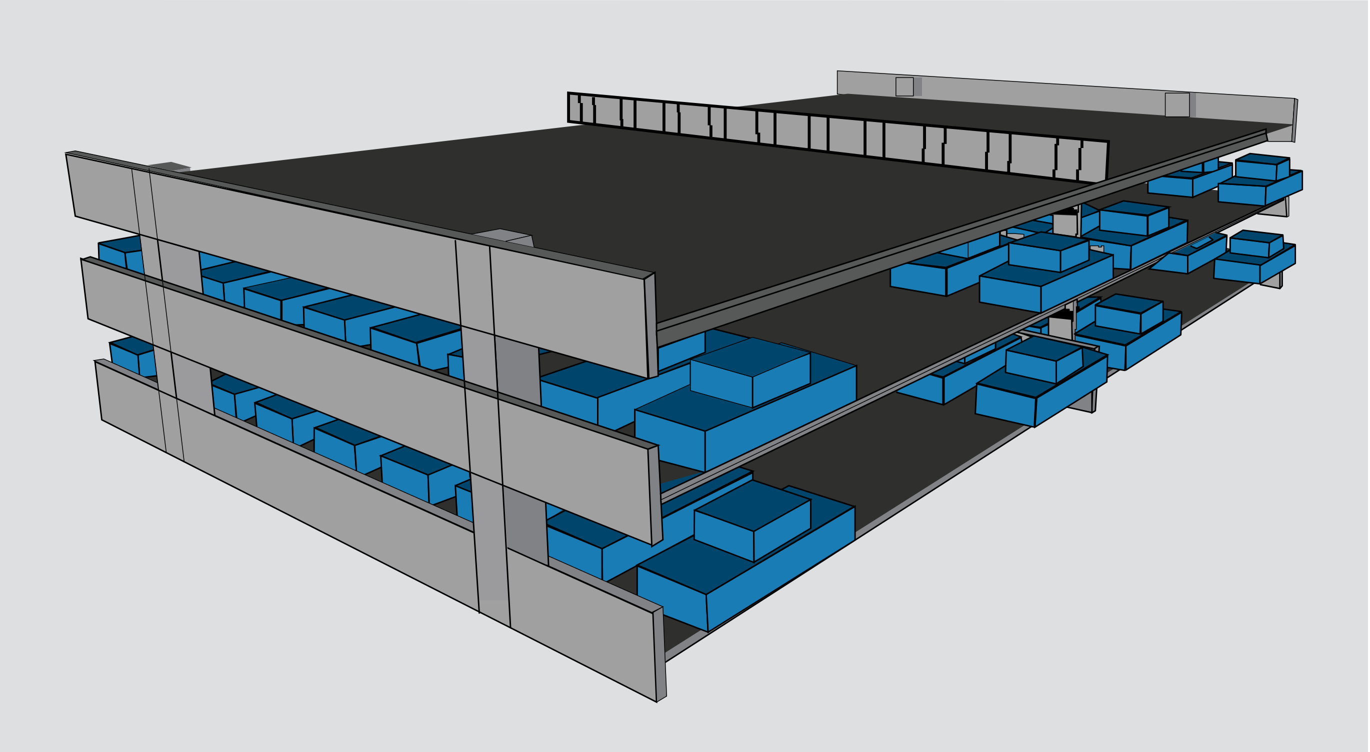

Figure 1. Fluid dynamics computer program model of the prototype parking structure.

The parking structure is constructed of precast concrete double-tee beams, pocketed spandrels, walls, and inverted-tee girders. Each bay comprises three double-tee beams that are oriented longitudinally north to south. The typical double tee is 4.6 m (15 ft) wide, 18.4 m (60 ft) long, and 0.87 m (34 in.) deep. The double tees are simply supported on the interior on corbels that protrude from the center wall or by inverted-tee girders. The exterior ends of the double tees are supported by pocketed spandrel beams. The precast concrete center wall includes a series of large openings.

Fire analysis models

Analysis was performed using a computational dynamics computer program. The computational fluid dynamics program is used to model the thermally driven turbulent flow of combustion gases in a fire. The program solves a version of the Navier-Stokes equations for low-speed (incompressible) flow.

Parking structure model

Figure 1 shows a typical fluid dynamics computer model of the prototype structure. The model includes a two-span transverse section of the structure composed of a full bay width plus one double-tee floor member from each adjacent bay. The model includes the following elements:

- solid components of the structure, which serve as obstructions to the flow of combustion gases
- vehicles parked in the structure, which serve as sources of fuel and as obstructions to the flow of combustion gases
- air spaces within and around the structure through which the combustion gases flow

The boundaries of the model include air space beyond the spandrel beams to capture combustion gases that exit the structure under the spandrel but reenter the structure at the floor above.

In the fluid dynamics computer program model, all components (structure, vehicles, and air spaces) have to be discretized using one uniform cell size. In general, building models in the fluid dynamics computer program require cell sizes of 100 to 150 mm (4 to 6 in.) for reasonable accuracy. Smaller cells can detract from the effectiveness of the large eddy simulation used by the fluid dynamics computer program to model convection, and larger cells are not fine enough to capture radiative effects of fire. Cell sizes of 100, 125, and 150 mm (4, 5, and 6 in.) were compared with the dimensions of the prototype structure. The 125 mm (5 in.) cells were found to most accurately accommodate the geometry, and as a result a 125 × 125 × 125 mm (5 × 5 × 5 in.) cell was used to create the model.

Vehicle model

Khono et al.[2] conducted a series of fire tests on eight vehicles, all of which were manufactured in the early to mid-1990s. Measured peak heat flux values ranged from

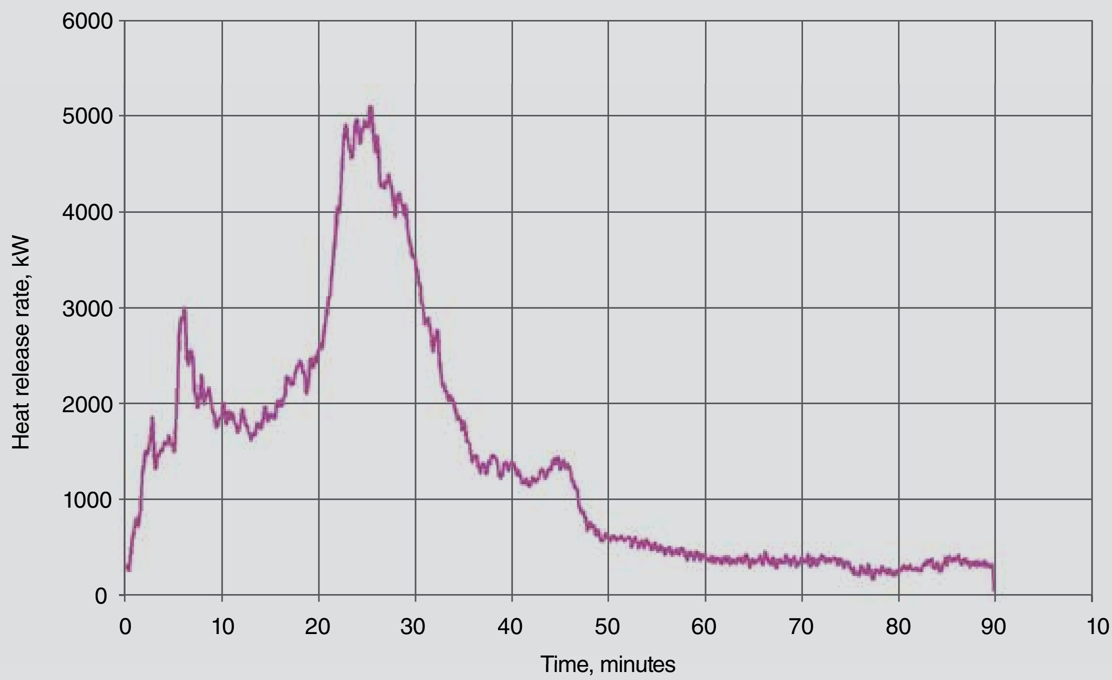

Figure 2. Heat flux record from fire test of vehicle 1.

2.44 to 6.76 MW, and total heat release ranged from 4.47 to 8.51 GJ. The analyses in this paper are based on the vehicle fire test result in **Fig. 2** (hereafter referred to as vehicle 1), a 1995 sport utility vehicle. Vehicle 1 has a total energy release of 7.40 GJ and a peak heat flux of 5100 kW.

An idealized vehicle geometry was generated to conform to the 125 mm (5 in.) mesh. The body of the vehicle was approximated by a rectangular prism 4.5 m (15 ft) long, 1.75 m (5.7 ft) wide, and 1 m (3.3 ft) high. A 125 mm (5 in.) thick plate that was 1.75 m (5.7 ft) long and 1.5 m (4.9 ft) wide was centered 0.5 m (1.6 ft) over the body to represent the roof of the cab of the vehicle (**Fig. 3**). All surfaces in the model were considered to be inert. The fire was modeled in the fluid dynamics computer program as a flat surface called a burner and was distributed over the area that would be taken up by the cab in a real vehicle as shown in the model. The burner was modeled as a flammable solid vent with a specified heat flux time-history equal to the heat release record from the vehicle fire test (Fig. 2).

Analysis variables

Nine fire analyses were performed in this research. This paper focuses on three analyses that examined the influence of center-wall-opening position, and single- versus multiple-vehicle fires, on the resulting fire load. The analysis matrix (**Table 1**) is described in the following paragraphs.

Center-wall-opening position

The center wall of the prototype parking structure comprises precast concrete sections with large openings (1.5 m [4.9 ft] wide × 1.7 m [5.6 ft] high) at regular intervals centered on the double-tee beams. Because the elevation of the double tees varies along the driving ramps, the relative position of the center-wall openings varies in relation to the underside of the double-tee beam flange along the length of the structure. The placement of these openings in the center wall influences how combustion gases pass from one side of the parking structure to the other and potentially from one floor to the next, depending on the elevation of the double-tee beams relative to the openings.

This paper addresses two different wall-opening positions. In the top-opening position (analysis 1), the top of the center-wall opening is flush with the bottom of the double-tee beam flange above the fire floor. In the bottom-opening position (analysis 2), the bottom of the center-wall opening is flush with the top of the slab of the fire floor. In analysis 1, combustion gases between the stems of the double-tee beam are free to flow in the north-south direction through the center-wall opening. In contrast, in analysis 2, this path is obstructed by the center wall.

Single- versus multiple-vehicle fires

Figure 4 shows vehicle positions on a typical floor. The figure shows a plan view section through the model at the elevation of the stems of the double-tee floor beams. The vehicles are shown in green in the parking stalls. In all analyses, the

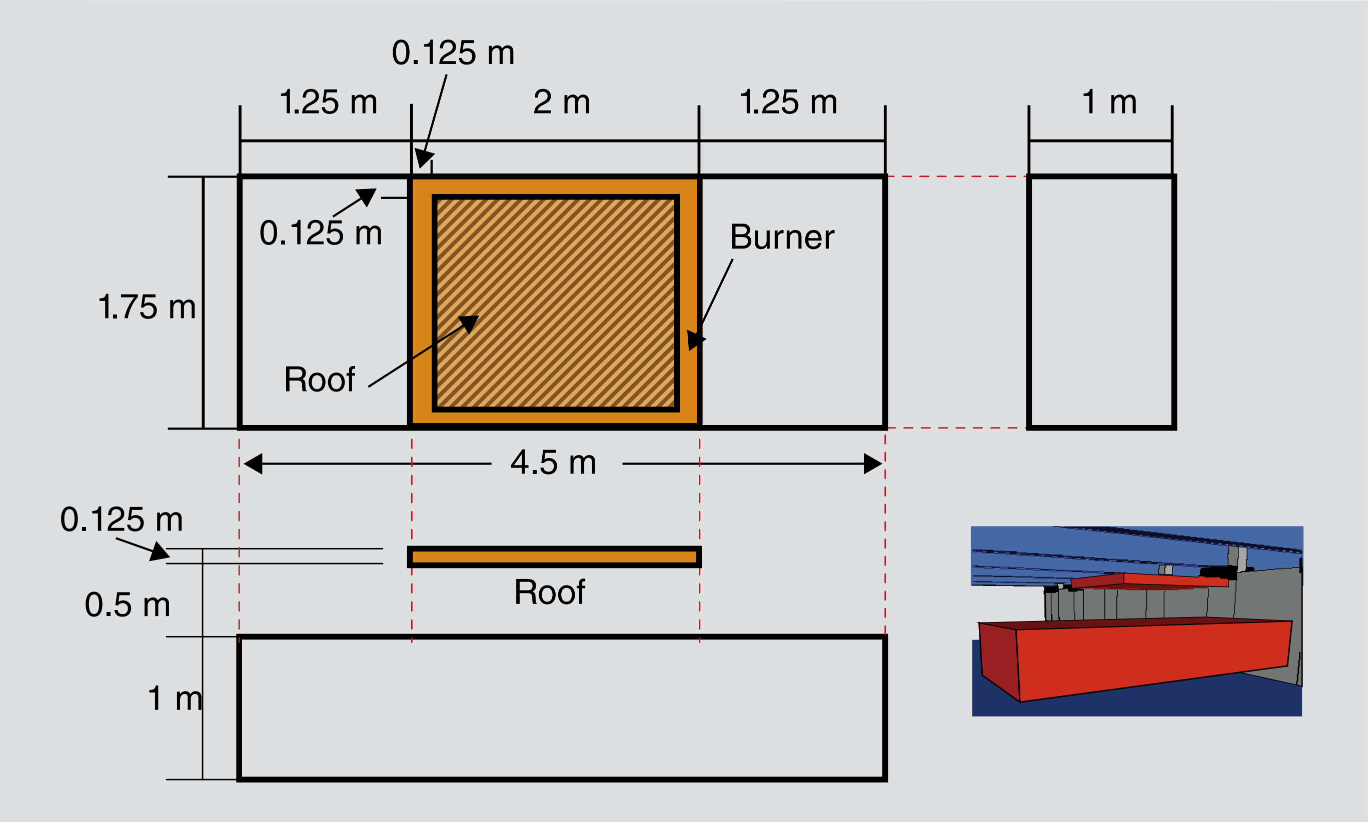

Figure 3. Fluid dynamics computer model of the vehicles. Note: 1 m = 3.28 ft.

fire initiates at position 23 (vehicle shown in red). Analyses 1 and 2 involve a single-vehicle fire at position 23. Analysis 9 addresses fire spread on a single floor with seven vehicles involved. The first vehicle in position 23 ignites at time 0, followed by vehicles at positions 22 and 24 at 12 minutes, vehicles at positions 21 and 25 at 24 minutes, and vehicles at positions 20 and 26 at 36 minutes. In analysis 9, the bottom of the center-wall opening is flush with the top of the slab of the fire floor (same as analysis 2), so the effect of single- versus multiple-vehicle fires can be evaluated by comparing analyses 2 and 9.

Computation details

A total of 2,764,800 cells (each measuring 125 × 125 × 125 mm [5 × 5 × 5 in.]) were used to construct an entire model (structure, vehicles, and air spaces). The fire analyses were conducted on an eight-node computer cluster comprising four dual-processor machines with two 64-bit processors in each running at 2.4 GHz and 1 GB RAM. Each analysis took approximately three weeks to execute.

Table 1. Analysis matrix for the fluid dynamics program analyses

Analysis	Center wall opening position	Vehicle fire characteristics	
		Position	Ignition time, minutes
1	Top	23	0
2	Bottom	23	0
9	Bottom	23	0
		22, 24	+12
		21, 25	+24
		20, 26	+36

Fire analysis output

In the fluid dynamics computer analyses, *instrumentation* refers to the specification of what analysis output is saved. There are several ways that each model is instrumented: thermocouples and slice files to capture gas temperatures and boundary files to capture heat flux impinging on the structure. The term *thermocouple* is used in the fluid dynamics computer program as a generic term to describe a sensor that records gas data at a specific point. Basically, this is how the locations at which analysis output is saved are specified. Thermocouples were placed at several locations (**Fig. 5**). All of the thermocouples were placed in the air space 125 mm (5 in.) below the bottom flange of the double-tee beam above the fire floor (that is, at z = 3.625 m [11.9 ft] in Fig. 5).

Slice files in the fluid dynamics computer model are used to gather the same information as thermocouples, but instead of outputting the temperature for a specific point, the slice file is used to graphically display the data on a specific plane (or slice).

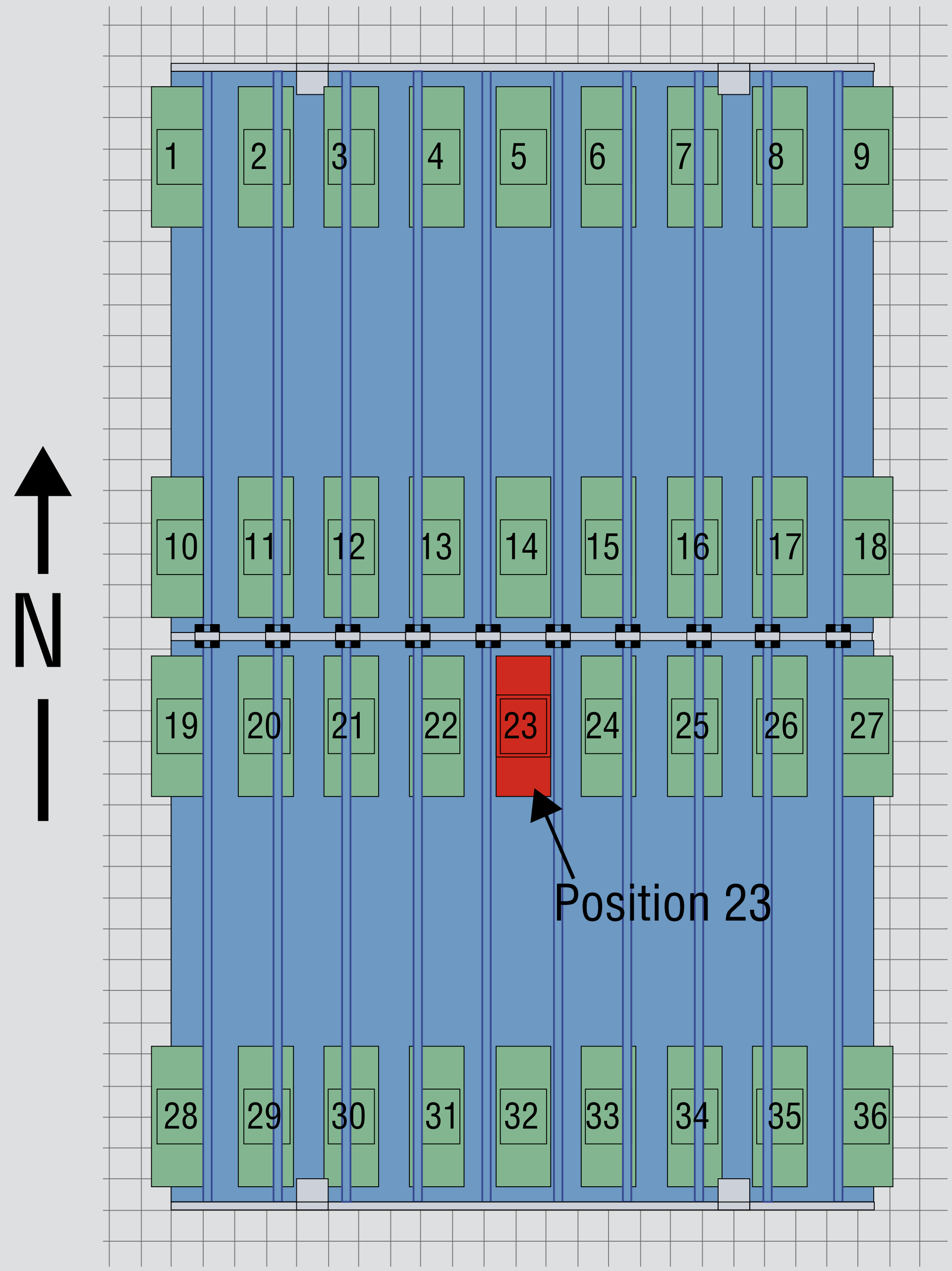

Figure 4. Plan view showing vehicle positions.

Finally, heat flux data were gathered in the fluid dynamics computer model by using boundary files. These files record heat flux into the structure. For this research, heat flux data into solid surfaces were gathered for all surfaces in the model at 30-second intervals. As described in the next section, the heat flux data for the double-tee beams were used in subsequent heat transfer finite element analyses to predict the temperatures of the prestressing strands.

Heat transfer models

The net heat flux output from the fluid dynamics computer program was used as input in a nonlinear finite element heat transfer analysis to determine the temperatures in the concrete at the locations of the prestressing strands in the double-tee floor members. A finite element model (FEM) of a double-tee stem and adjacent flange was constructed based on the dimensions of the 15DT34 double-tee from the *PCI Design Handbook: Precast and Prestressed Concrete*[6] and the 188-S strand pattern (18 strands of ½ in. [12 mm] diameter). **Figure 6** shows the FEM and 15DT34 section.

The element type was a solid (continuum), first order (eight nodes), hexahedra (brick) element with full integration. The element mesh configuration was eight elements

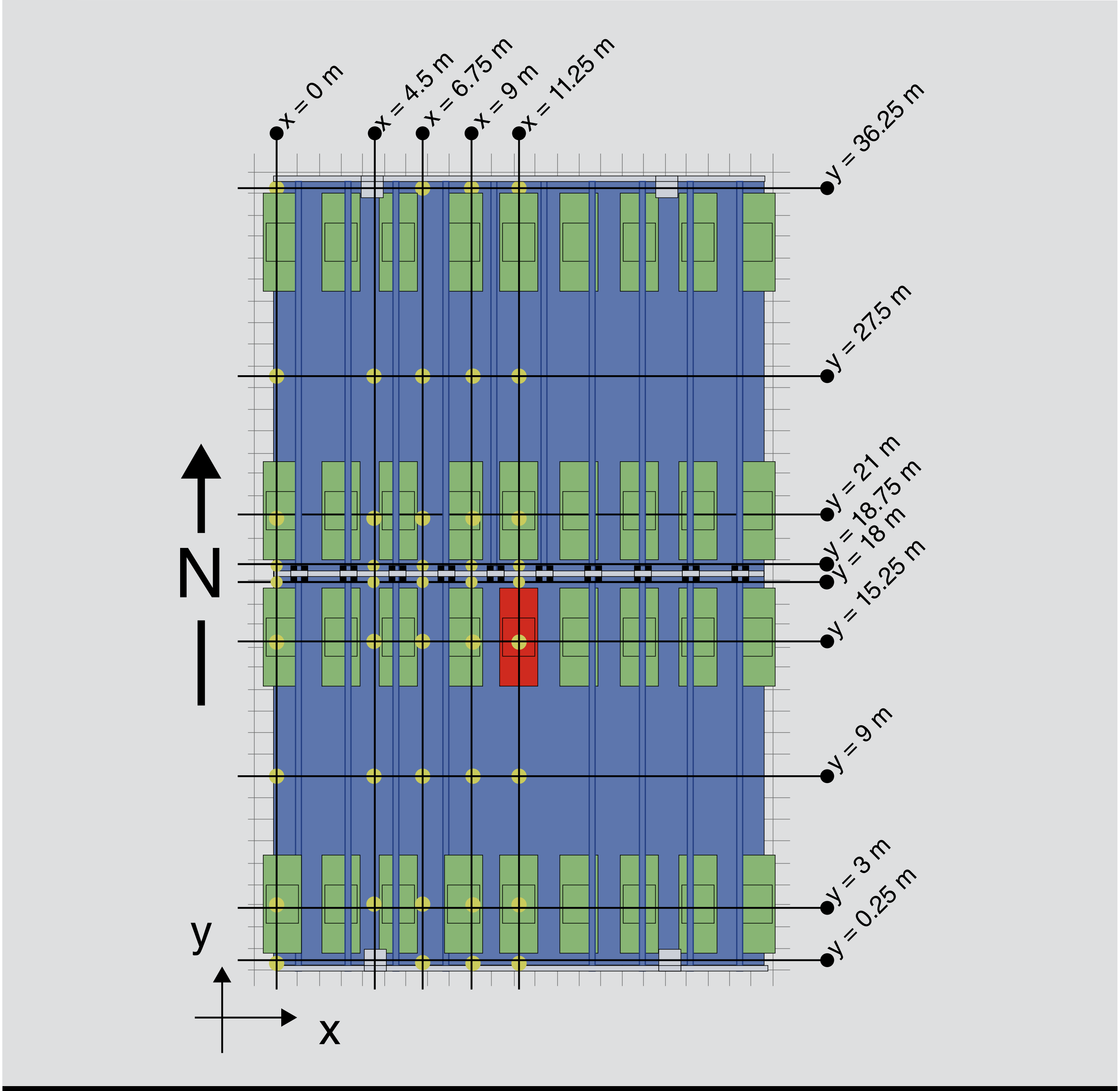

Figure 5. Plan view showing x- and y-coordinates of thermocouples. Note: All at z = 3.625 m or 0.125 m below the bottom of the double-tee flange of beam above the fire floor. 1 m = 3.28 ft.

across the stem and four through the thickness of the slab.

The element mesh configuration results in nodes located at the levels of the prestressing strands in the stem. Assuming that concrete and prestressing strand temperatures are the same at each location (the usual assumption), this allows prestressing steel temperatures to be determined from the analyses.

As a final step, the equations for reduction in strength in prestressing steel from Eurocode 1[7] were used to estimate the temperature-reduced strength $f_{pu\Theta}$. Bayreuther and Pessiki[1] give complete details of the heat transfer finite element analyses and prestressing steel strength reduction calculations.

Results and discussion

Table 2 summarizes key response quantities from analyses 1, 2, and 9. Included in the table for each analysis is the peak gas temperature obtained from the computational fluid dynamic analysis, peak prestressing steel temperature obtained from the FEM analysis, and the temperature-reduced strength of the prestressing steel $f_{pu\Theta}$ computed using Eurocode 1 and the steel temperatures from the FEM analysis. The prestressing steel temperature and strength

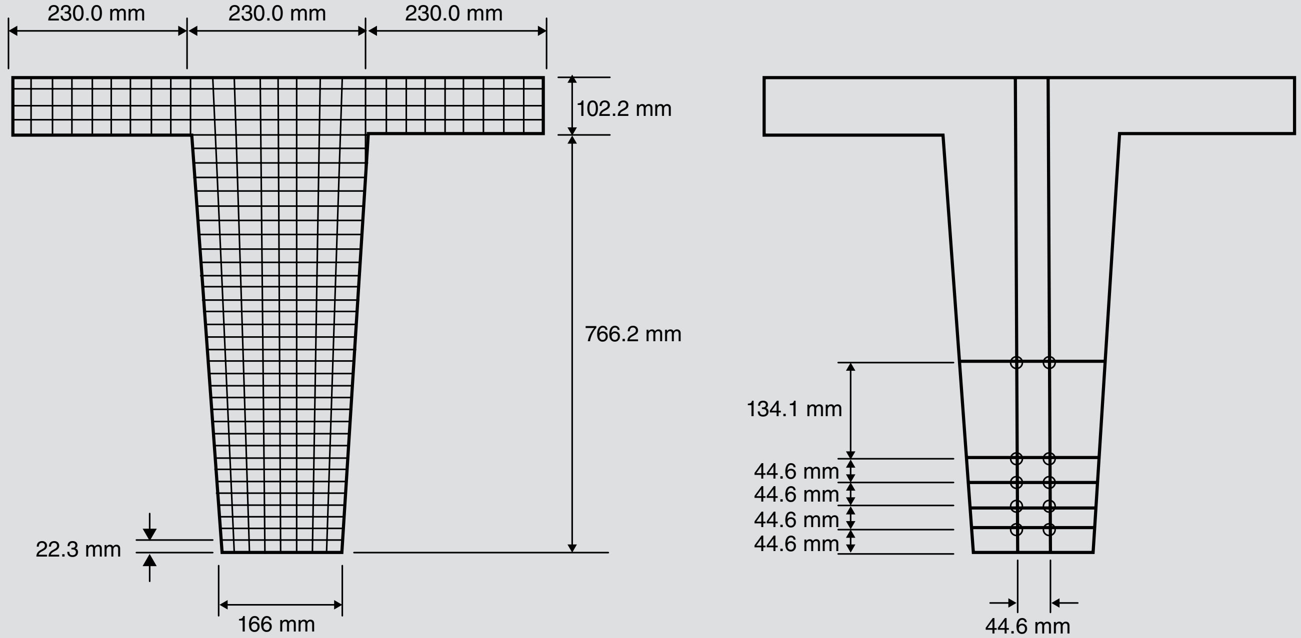

Figure 6. Finite element mesh and double-tee model dimensions (left) and PCI prestressing strand pattern 188-S (right). Note: 1 mm = 0.0394 in.

are reported for the bottom layer of strand, where the temperature increase was the greatest.

Influence of center-wall-opening position

Figures 7 and **8** show the gas temperature time histories from analyses 1 and 2, respectively, 125 mm (5 in.) below the flange of the double-tee beam above the fire floor. The thermocouples were all centered between the stems of the double tee over location 23 (that is, at x = 11.25 m [37 ft]), where the fire initiates. The y coordinate of each thermocouple indicates its position along the double tee. The y coordinate equal to 250 mm (10 in.) was adjacent to the exterior spandrel, y = 18.0 m (59 ft) was adjacent to the center wall, and y = 15.25 m (50 ft) was directly above vehicle 23 (Fig. 5). Thus all results in Fig. 7 and 8 were plotted on the north side of the center wall. Similarly, **Fig. 9** and **10** show gas temperature results from analyses 1 and 2 for the south side of the center wall.

The gas temperatures obtained on the north side of the center wall in analyses 1 and 2 are similar (Fig. 7 and 8). In both cases, the peak gas temperature occurred directly above vehicle 23 and reached a value of approximately 1000˚C (1800˚F). The gas temperatures changed rapidly, and data were saved at 15-second intervals during each analysis. As a result, the actual peak values may not have been captured, but over the span of several minutes the trends in temperature are thought to be correct and the reported peak values approximately correct.

The gas temperatures on the south side of the center wall in analyses 1 and 2 differed greatly. As expected, the gas temperatures in analysis 1 (top opening) on the south side of the center wall were higher than those in analysis 2

Table 2. Maximum prestressing steel temperatures at bottom level of strand and corresponding reductions in strength

Analysis	Maximum combustion gas temperature, ˚C	Maximum prestressing steel temperature, ˚C	$f_{pu\Theta}$, MPa	$f_{pu\Theta}/f_p$
Baseline condition (before fire)	n/a	20	1860	1.00
1	1019	142	1747	0.94
2	971	142	1747	0.94
9	890	214	1579	0.85

Note: f_{pu} = strength of prestressing steel; $f_{pu\Theta}$ = temperature-reduced strength of the prestressing steel; n/a = not applicable. 1 MPa = 0.145 ksi; ˚F = (˚C)(9/5) + 32.

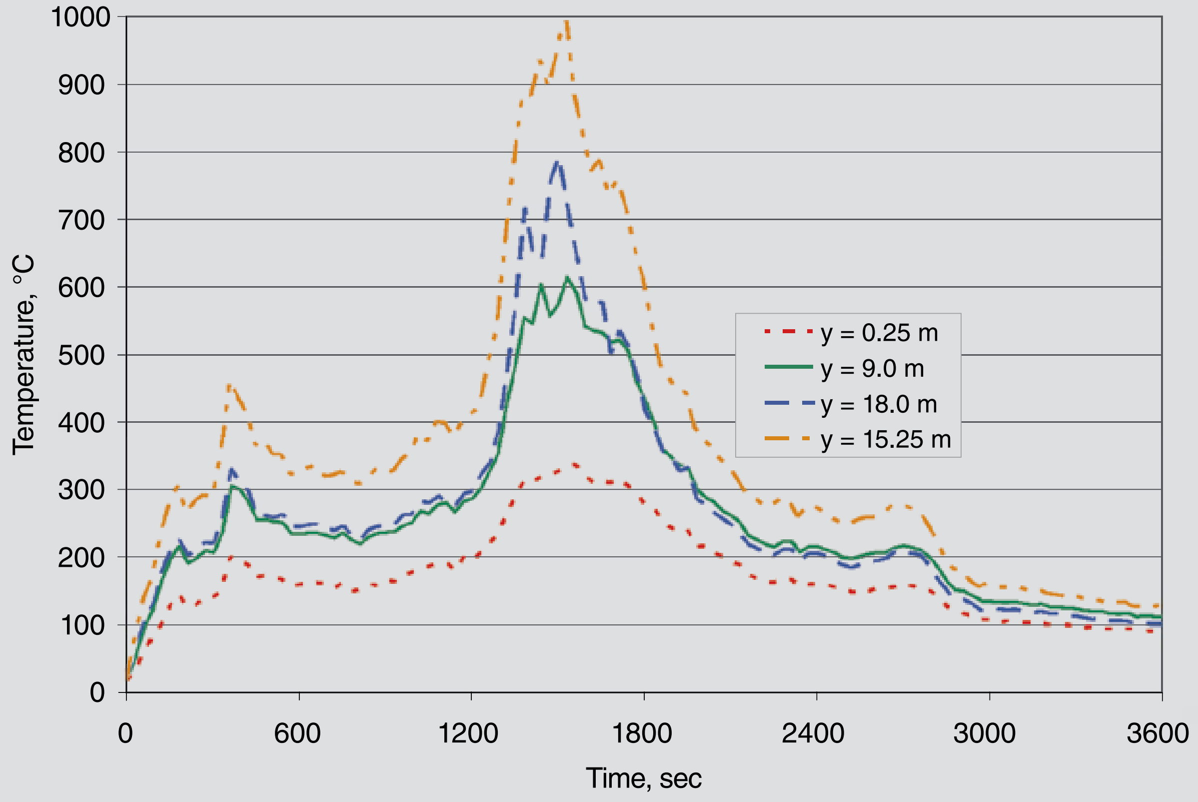

Figure 7 Gas temperature histories for analysis 1 (top opening) centered between double-tee stems above burning vehicle at x = 11.25 m, z = 3.625 m. Note: 1 m = 3.28 ft; °F = (°C)(9/5) + 32.

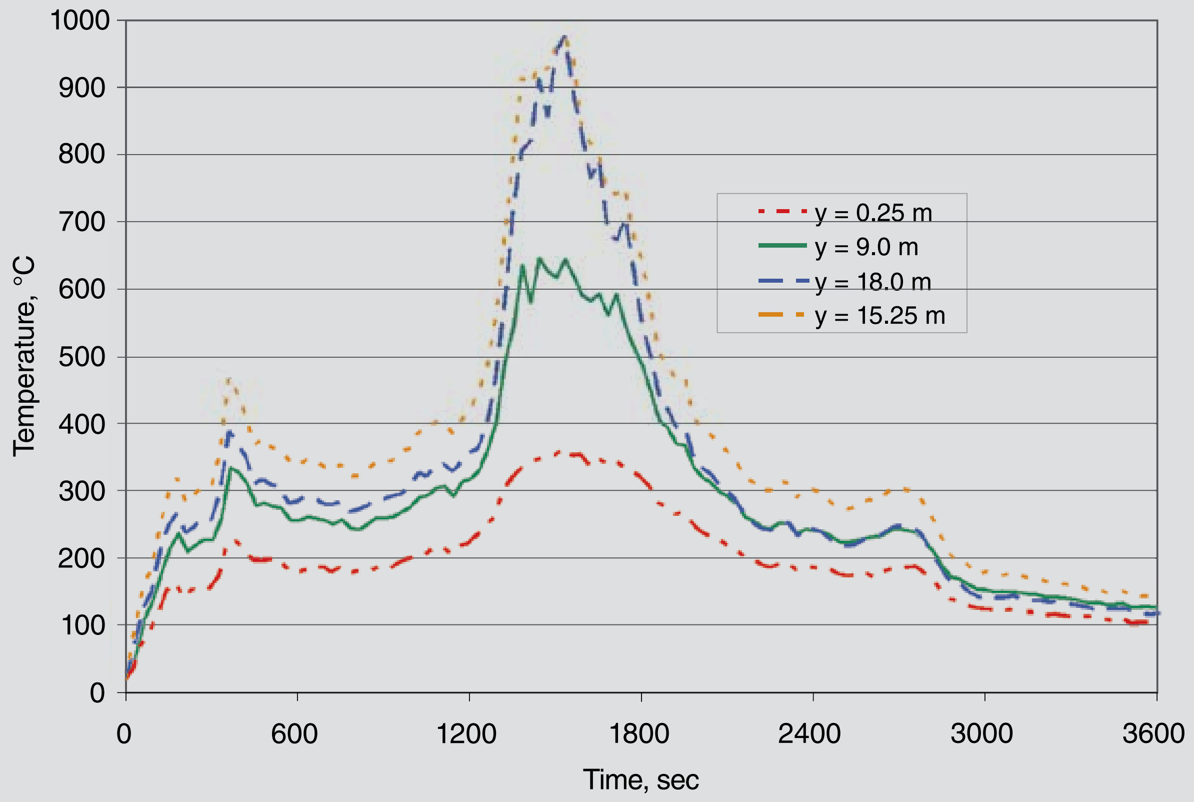

Figure 8. Gas temperature histories for analysis 2 (bottom opening) centered between double-tee stems above burning vehicle at x = 11.25 m, z = 3.625 m. Note: 1 m = 3.28 ft; °F = (°C)(9/5) + 32.

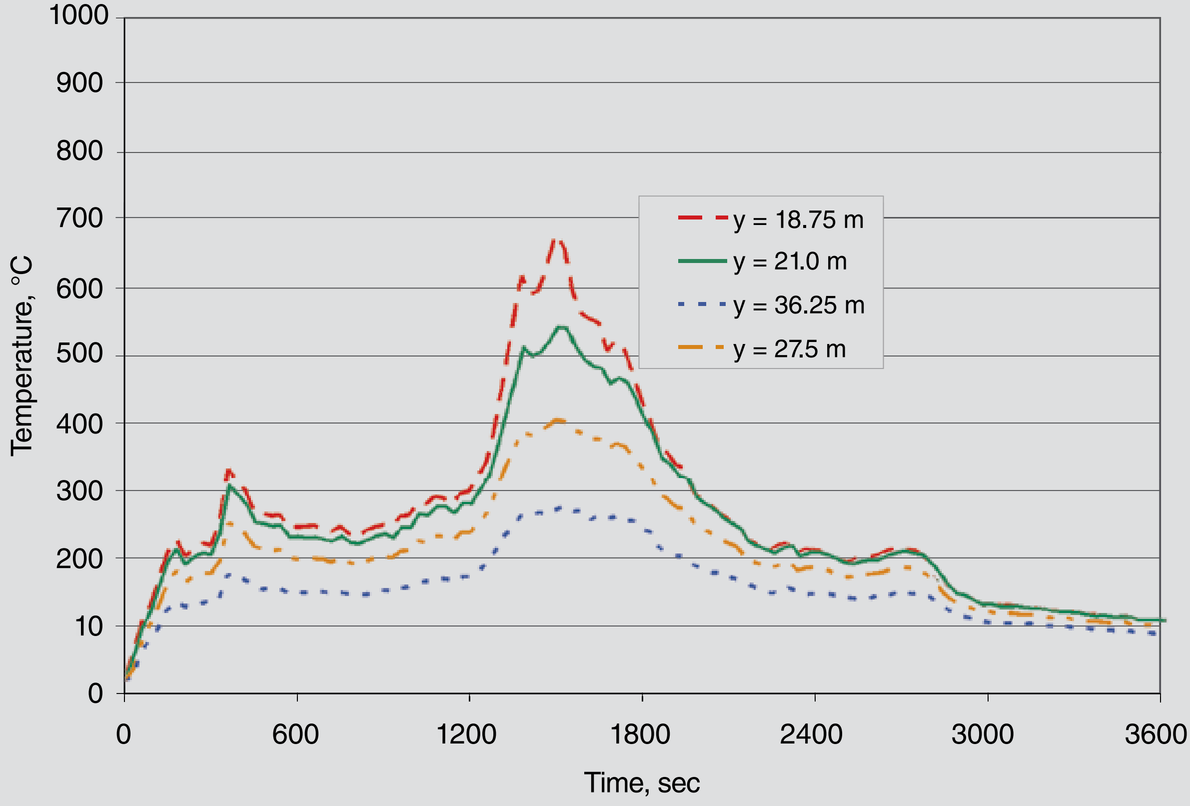

Figure 9. Gas temperature histories for analysis 1 (top opening) centered between double-tee stems above burning vehicle at x = 11.25 m, z = 3.625 m. Note: 1 m = 3.28 ft; °F = (°C)(9/5) + 32.

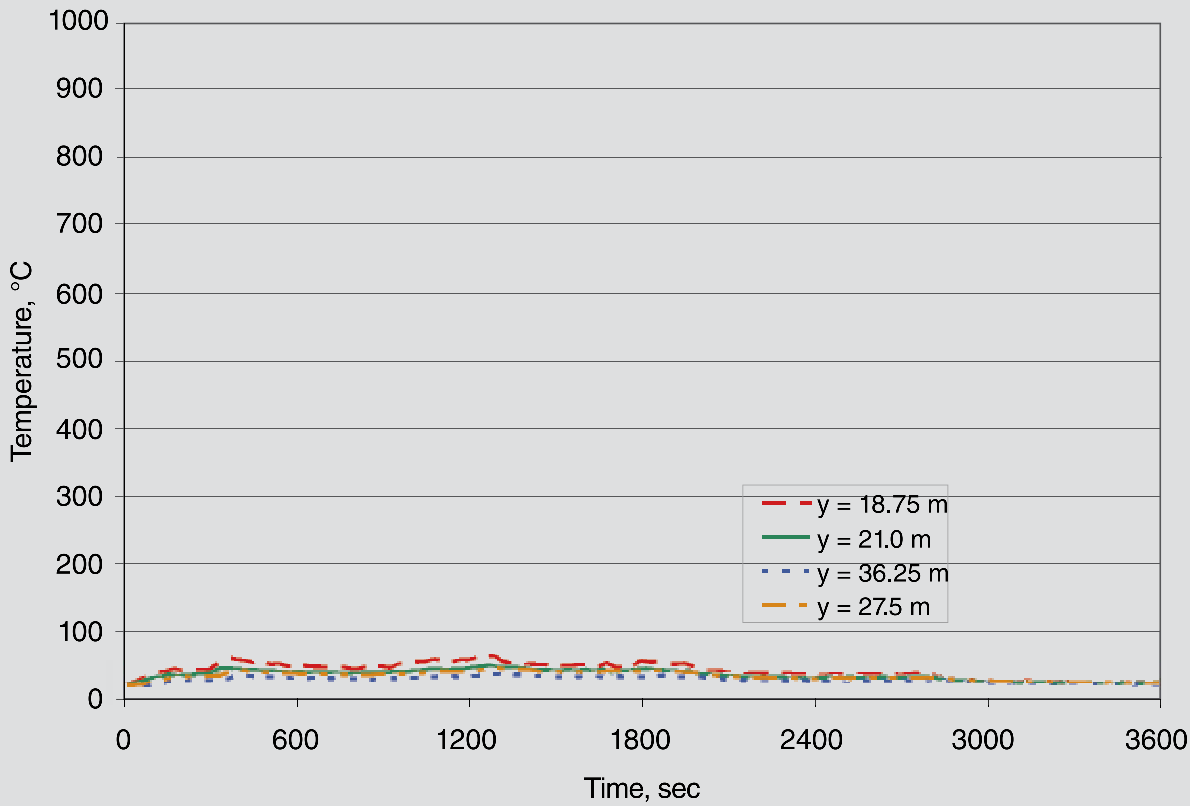

Figure 10. Gas temperature histories for analysis 2 (bottom opening) centered between double-tee stems above burning vehicle at x = 11.25 m, z = 3.625 m. Note: 1 m = 3.28 ft; °F = (°C)(9/5) + 32.

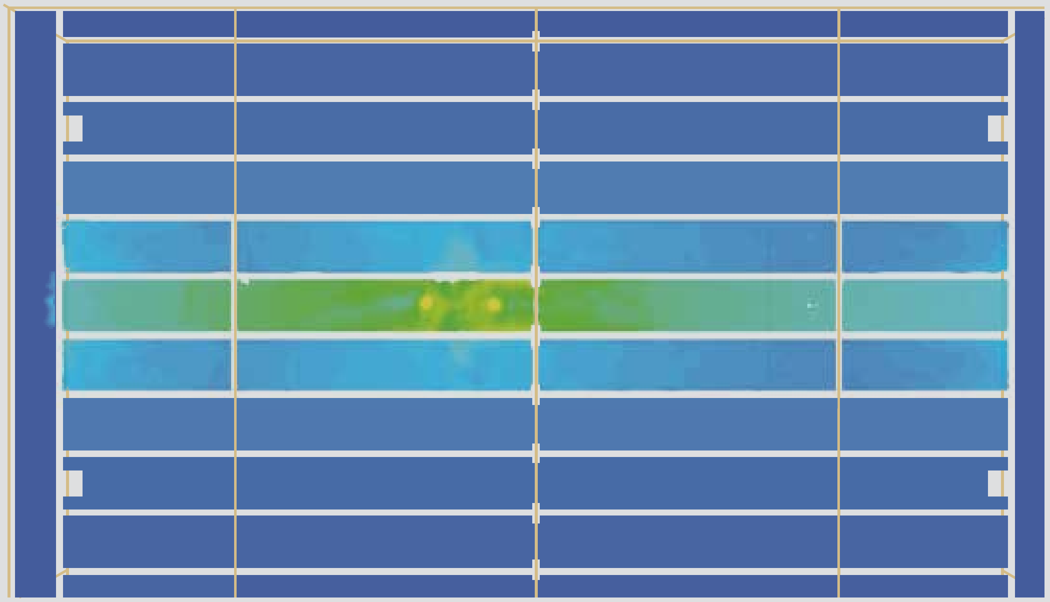

Figure 11. Analysis 1 (top opening) gas temperature image at 1800 seconds.

(bottom opening) because the top opening allowed the combustion gases to flow unobstructed from the north to the south side of the structure (Fig. 9 and 10).

Figures 11 and **12** show slice files of the temperature distributions 125 mm (5 in.) below the flange of the double-tee beam above the fire for analyses 1 and 2, respectively, at an elapsed time of 1800 seconds from the initiation of the fire. The figures show how combustion gases flowed freely across the center wall opening in analysis 1 (top opening) but were obstructed by the center wall in analysis 2 (bottom opening).

Finally, Table 2 shows that for both the top-opening and bottom-opening cases, the maximum prestressing steel temperatures were the same, and the reductions in prestressing steel strength were only about 6%.

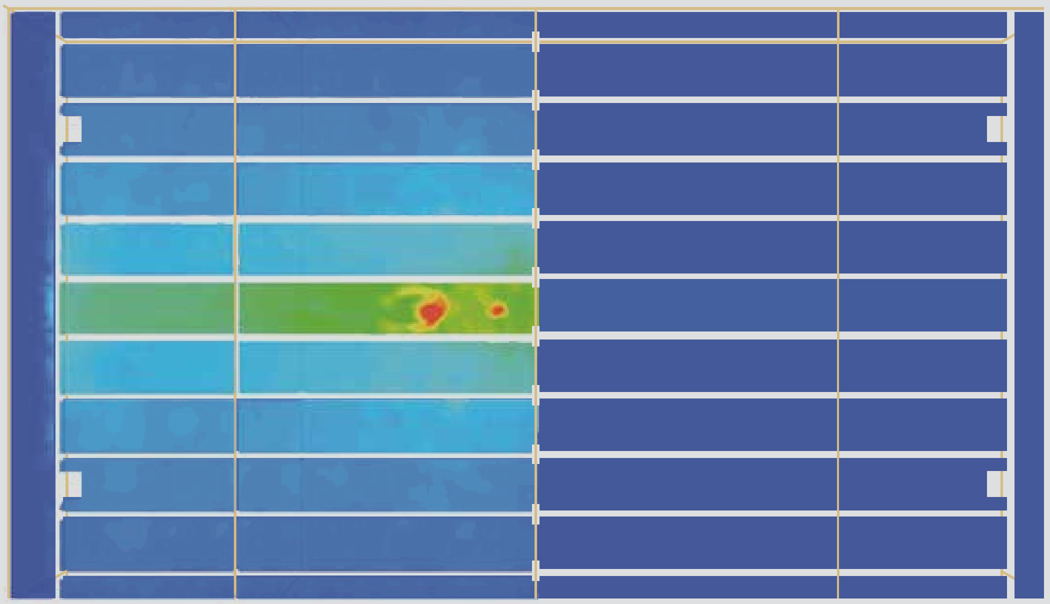

Figure 12. Analysis 2 (bottom opening) gas temperature image at 1800 seconds.

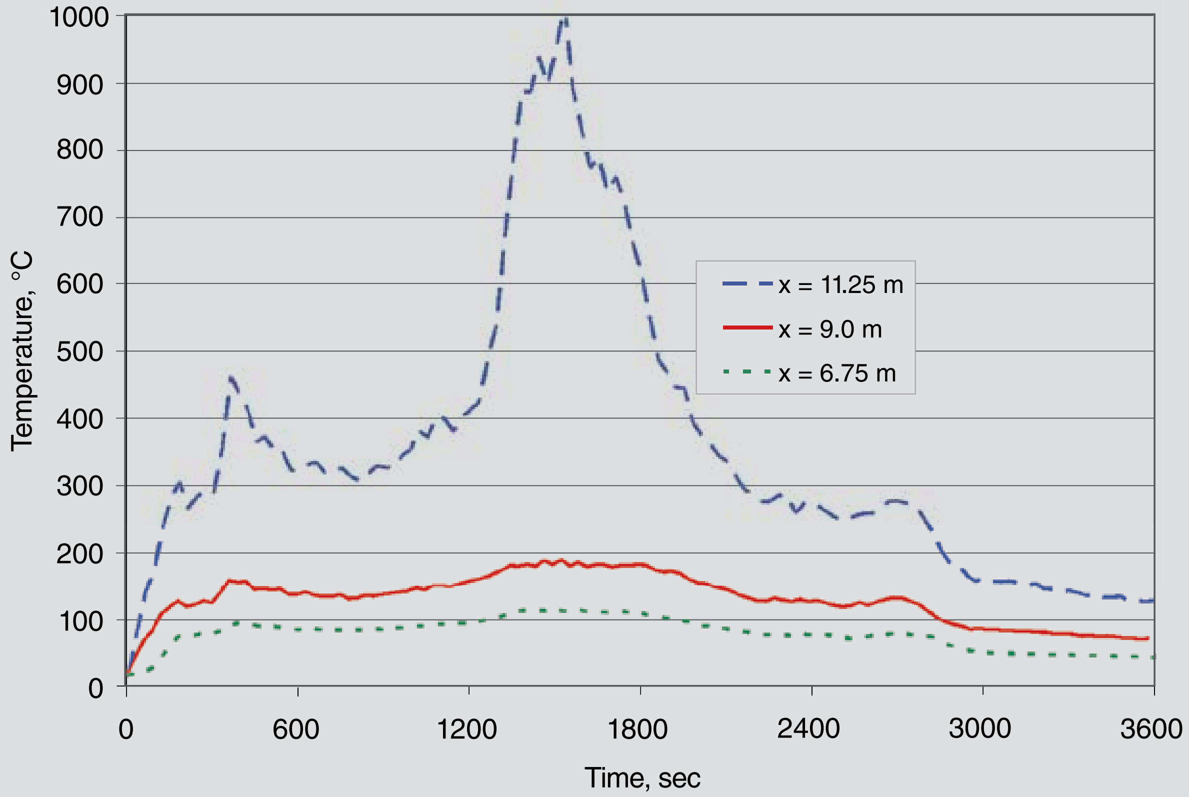

Figure 13. Gas temperature histories for analysis 1 (top opening) centered between adjacent double-tee stems at y = 15.25 m, z = 3.625 m. Note: 1 m = 3.28 ft; ˚F = (˚C)(9/5) + 32.

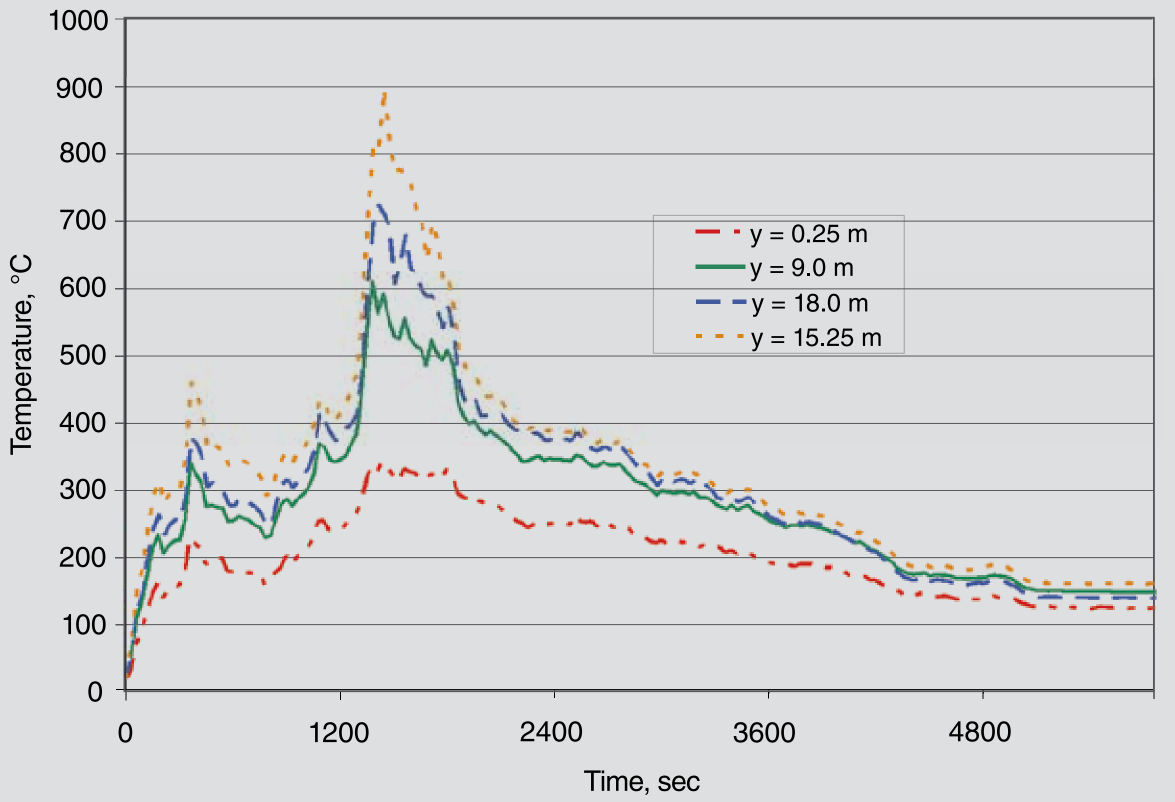

Figure 14. Gas temperature histories for analysis 9 (multivehicle) centered between double-tee stems above burning vehicle at x = 11.25 m, z = 3.625 m. Note: 1 m = 3.28 ft; ˚F = (˚C)(9/5) + 32.

Influence of double-tee stems

Like the center wall, the stems of the double-tee beams impeded the flow of combustion gases in the structure. **Figure 13** shows gas temperature results from analysis 1 between the double-tee stems at increasing distances from the fire initiation site at location 23. The figure illustrates how rapidly the temperature decreased and thus how effectively the stems limited the spread of hot combustion gases transverse to the span of the double-tee beams. This can also be seen in Fig. 11 and 12.

Influence of multiple-vehicle fires

Figure 14 shows the gas temperature history from analysis 9, 125 mm (5 in.) below the flange of the double-tee beam above the fire floor. Similar to Fig. 8 (analysis 2), the thermocouples were all centered between the stems of the double tee over location 23 (that is, at x equal to 11.25 m [37 ft]). As explained earlier, in both analysis 2 and analysis 9, the bottom of the center-wall opening is flush with the top of the floor slab.

A comparison of Fig. 14 and 8 shows that the peak temperature was actually higher in the single-vehicle fire. This result is surprising, and is thought to result from increased turbulence in the multivehicle fire, which caused greater dispersion of the combustion gases throughout the structure. It may also be due to the 15-second intervals at which temperatures were recorded.

Table 2 shows that the prestressing steel temperatures were considerably higher in the multivehicle fire compared with the single-vehicle fire. This is because the multivehicle fire maintains a high temperature longer than the single-vehicle fire, so the total energy imparted to the structure over time is greater in the multivehicle fire.

The highest steel temperature reached in any of the nine analyses[1] occurred in the bottom level of strand in analysis 9. The maximum temperature reached in the prestressing steel was 214˚C (417˚F). Table 2 also shows that, even for this severe fire, with no intervention to reduce or extinguish it, the predicted strength reduction in the prestressing steel is only about 15%.

Conclusion

The following conclusions are drawn from this study:

- The geometry of a precast concrete parking structure can have a significant effect on the movement of combustion gases in the structure. Depending on the position of the wall openings relative to the floor members, heat may be trapped on one side of the structure or allowed to flow freely from one side to the other or from one floor to the next. The stems of a double-tee beam create obstructions that impede the flow of combustion gases transverse to the span of the double-tee beam.

- Multivehicle fires cause greater increases in prestressing steel temperatures, and thus greater reductions in steel strength, than do single-vehicle fires.

- Even large multivehicle fires without intervention to reduce or extinguish them lead to only minor reductions in prestressing steel strength.

Acknowledgments

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References

1. Bayreuther, J. L., and S. Pessiki. 2006. "Analytical Investigation of Fire Loads for Precast Concrete Parking Structures." ATLSS (Advanced Technology for Large Structural Systems) report 06-19. Bethlehem, PA: ATLSS, Lehigh University.

2. Khono, M. 2005. "Vehicle Fire Research." Personal communication (November 8, 2005).

3. Mangs, J. O., and O. Keski-Rahkonen. 1994. "Characterization of the Fire Behavior of a Burning Passenger Vehicle. Part I: Vehicle Fire Experiments." *Fire Safety Journal* 23: 17–35.

4. Shipp, M., and M. Spearpoint. 1995. "Measurements of the Severity of Fires Involving Private Motor Vehicles." *Fire and Materials* 19: 143–151.

5. Zhao, B., and J. Kruppa. 2004. "Structural Behavior of an Open Vehicle Park under Real Fire Scenarios." *Fire and Materials* 28: 269–280.

6. PCI Industry Handbook Committee. 2004. *PCI Design Handbook: Precast and Prestressed Concrete*. MNL-120. 6th ed. Chicago, IL: PCI.

7. European Committee for Standardization. 2002. *EC1: Eurocode 1 Actions on Structures, Part 1*. London, UK: British Standards Institution.

Notation

E = energy release

f_{pu} = strength of prestressing steel

$f_{pu\Theta}$ = temperature-reduced strength of the prestressing steel

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Abstract

Research was performed to investigate the effects of vehicle fires in precast concrete parking structures. A typical precast concrete parking structure was analyzed for a series of vehicle fires, and the resulting fire loads (temperature and heat flux histories) at various locations in the structure were determined. Analysis parameters were systematically varied to explore a range of structure geometry and fire parameters (single- versus multivehicle fires). Analysis was performed using a computational fluid dynamics computer model. Heat flux histories obtained from the fluid dynamics computer model were used as input to subsequent finite element analyses to determine the temperature rise in the prestressing strand of the double-tee floor members. The increased prestressing steel temperatures were then used to estimate the reductions in steel strength. Results show that the geometry of the structure has a significant effect on heat transmission. For the nine fire scenarios considered, vehicle fires caused only minor reductions (maximum of 15%) in the strength of the prestressing steel of the double-tee floor members.

Keywords

Double tee, finite element analysis, fire, floor member, fluid dynamics, prestressing steel.

Review policy

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