Fire behaviour of steel members penetrating concrete walls

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ABSTRACT

In steel construction it is often desirable for a steel member to pass through a concrete fire wall rather than being curtailed at the wall. In situations where a steel member penetrates a fire wall, the member will usually be fire protected for a certain length on each side of the wall so as to minimise the heat flow through the steel member and reduce the likelihood of ignition of combustibles on the non-fire (unexposed) side within the adjacent compartment. The testing reported in this paper suggests that it is not necessary to apply fire protection to each side of a penetrating steel member since the resulting temperature rise of the member is insufficient to cause ignition.

KEYWORDS
Steel members; fire wall

1. Introduction

It is often desirable for structural steel members to pass through a fire wall or common wall rather than being curtailed on each side of the wall. In such cases, the penetrating member will often be fire protected for a certain length on each side of the wall so as to minimise the possibility of fire spread through heat conduction and excessive temperature rise of the member on the unexposed side of the wall. This latter aspect is necessary to ensure that lateral restraint will continue to be provided to the top of the wall by the member on the unexposed side of the wall, as illustrated in Fig.1. This lateral restraint is necessary to maintain the structural adequacy of the wall.

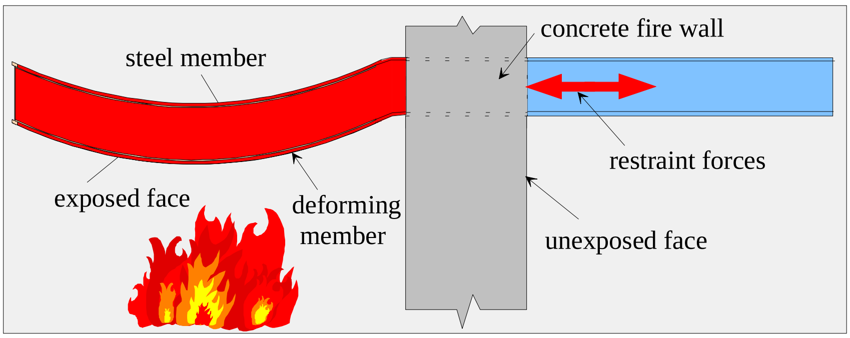


Fig. 1 - Lateral restraint from member on the unexposed side of the wall

Such fire protection can be costly and it is not clear that it is necessary. The reasons for this is that although a steel member is heated intensely on one side of a wall, this heat will be readily conducted to the unexposed side where it will be lost by radiation and convection to the surroundings. Some heat will also be conducted into the concrete wall. These mechanisms are illustrated in Fig.2. Transient heat flow analysis can be used to demonstrate dramatic temperature drop across the width of the wall but such calculations need to be confirmed experimentally.

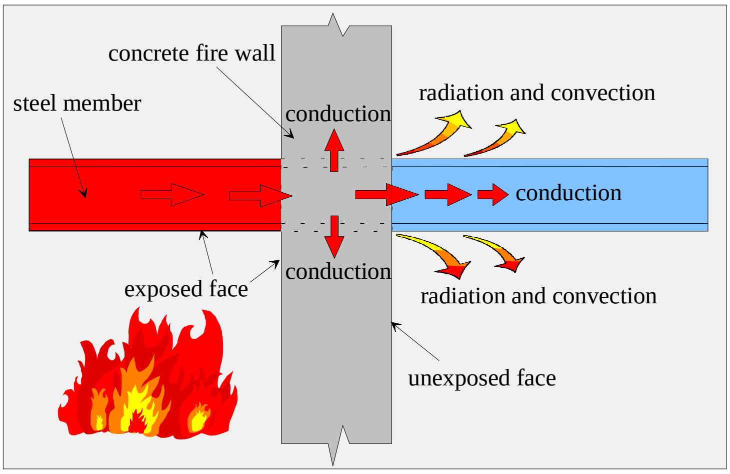


Fig. 2 - Mechanisms of heat transfer

The ability of a penetrating member to act as an effective bracing member depends on the temperature of the member on the unexposed side of the wall: if the member is too hot, it will have insufficient stiffness to provide effective restraint. Similarly, high temperatures could lead to ignition of combustibles should these be in contact with the members on the unexposed side.

The tests [1] described in this paper were undertaken to better assess the above situation. The tests were conducted at the Centre for Environmental Safety and Risk Engineering of Victoria University of Technology.

2. Test set-up, test specimens and instrumentations

2.1 Test Set-up

The tests were conducted in a standard fire test furnace which internally measures 2.1 m width × 1.8 m depth × 2.1 m height. Fig.3 shows an overall view of the furnace with two test specimens mounted in the side walls of the furnace.

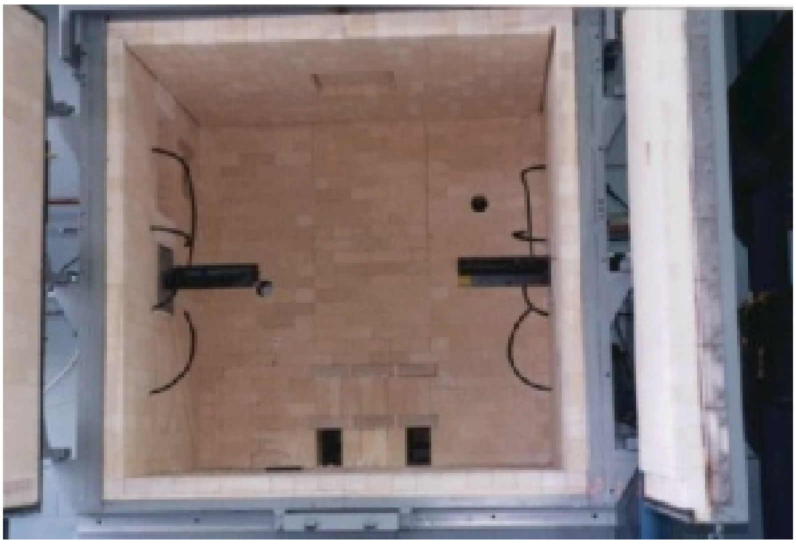


Fig. 3 - Overall view of test set-up

Fig. 4 shows details of test specimen mounted in the side walls of the furnace.

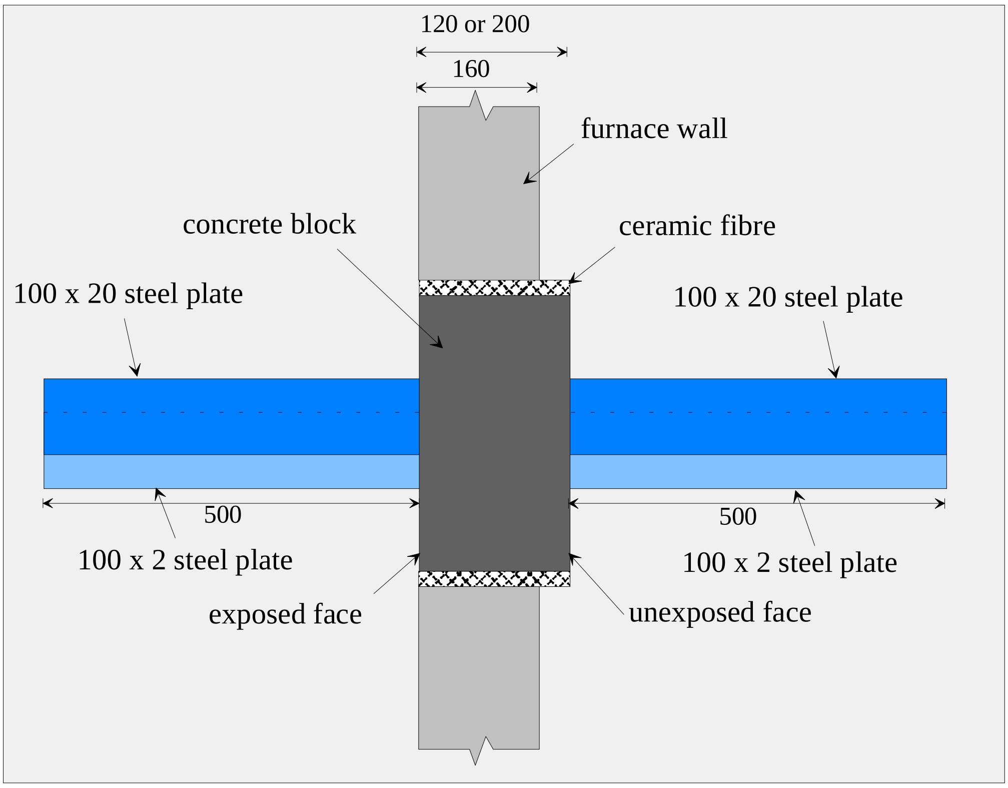


Fig. 4 - Layout of test set-up

2.2 Test Specimens

A total of eight specimens were tested in a series of four tests, each test having two specimens, with one specimen placed in one wall of the furnace and the other in the opposite wall. Each test specimen contained two steel plates, one with dimensions of 2 mm thick x 100 mm wide x 1200 mm long and the other having dimensions of 20 mm thick x 100 mm wide x 1200 mm long. A concrete block of dimensions 365 mm x 385 mm x 120 mm (or 200 mm) thick was cast around the middle section of the length of the steel plates. The concrete block was considered to simulate a fire wall, and the plates chosen simulate the web or flange of a rolled section (in the case of the 20 mm plate) and a purlin penetrating the wall (in the case of the 2 mm plate).

Four specimens were cast in the horizontal position (i.e. with the steel plate vertical) so good compaction of the concrete was obtained. The concrete blocks for the other four specimens were cast with holes to allow grouting of the steel plates once they were located. For two of these specimens, the voids were grouted when the blocks were in the vertical position to simulate a situation that may occur on site. The other two specimens were grouted with the blocks in the horizontal position. Fig. 5 shows the dimensions of a typical specimen with the position of the steel plates and voids in relation to the concrete block. Photographs of the test specimens are given in Table 1.

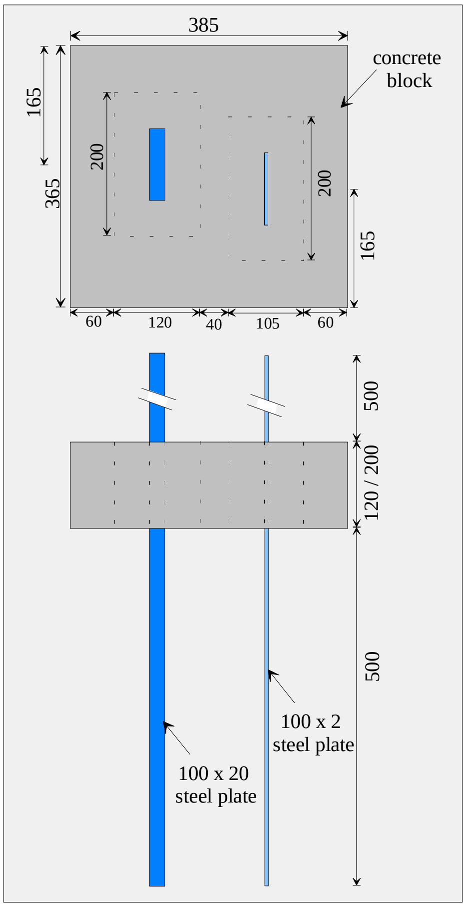


Fig. 5- Details of test specimens

Table 1 gives a summary of the configuration of the test specimens. A general layout of the test specimens is given in Fig. 6.

Table 1 - Configuration of test specimens

Specimen No.	Specimen Configuration	Remarks
VUT033A		Voids filled insitu with concrete block. Steel members positioned, and voids grouted with concrete mix with concrete block placed horizontally. Thickness of concrete block = 120 mm.
VUT033B		Voids filled insitu with concrete block. Steel members positioned, and voids grouted with concrete mix with concrete block placed vertically. Thickness of concrete block = 120 mm.
VUT034A		Voids filled insitu with concrete block. Steel members positioned, and voids grouted with concrete mix with concrete block placed horizontally. Thickness of concrete block = 200 mm.

VUT034B		Voids filled insitu with concrete block. Steel members positioned, and voids grouted with concrete mix with concrete block placed vertically. Thickness of concrete block = 200 mm.
VUT035A		No voids. Steel members cast insitu with the concrete block. Thickness of concrete block = 120 mm.
VUT035B		No voids. Steel members cast insitu with the concrete block. Thickness of concrete block = 120 mm.
VUT036A		No voids. Steel members cast insitu with the concrete block. Thickness of concrete block = 200 mm.
VUT036B		No voids. Steel members cast insitu with the concrete block. Thickness of concrete block = 200 mm.

(a) Voids grouted vertically (b) Voids grouted horizontally

Fig. 6 - Grouting of voids in test specimens

2.3 Instrumentation

Type K mineral insulated thermocouples were used to measure furnace temperatures throughout the tests. The steel temperatures were measured using spot-welded thermocouples attached to the sides and edges of the steel plates. The thermocouple positions are shown in Fig. 7. The positions of furnace thermocouples are also shown in Fig. 7. Copper-disc thermocouples were also attached to the unexposed face of the concrete block to measure the temperatures of the concrete.

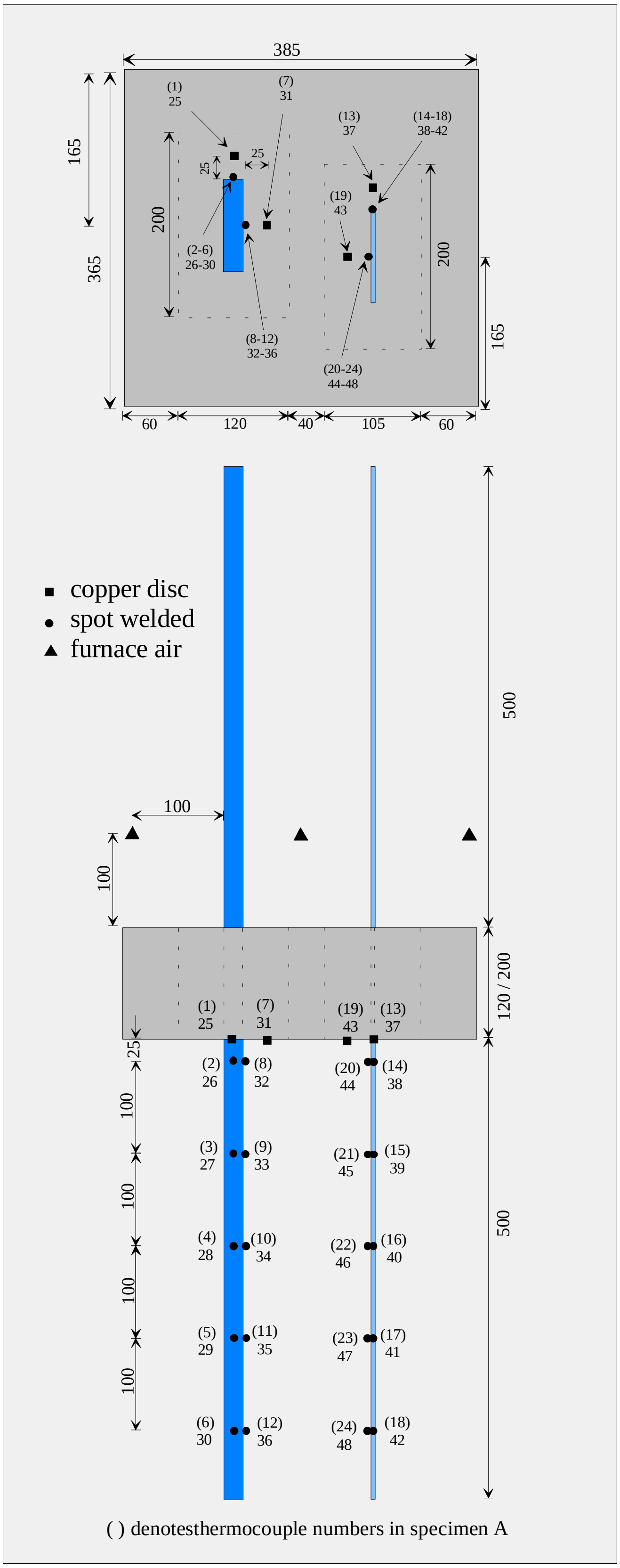
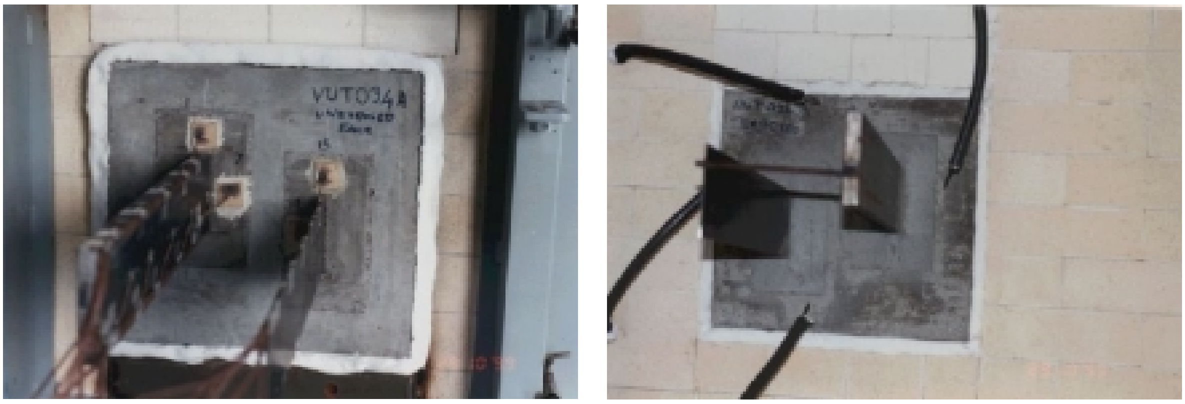


Fig. 7 - Thermocouples Positions

Figs 8(a) and (b) show the unexposed and exposed faces of a test specimen positioned on one side of the furnace wall with its associated thermocouples.



(a) Thermocouples at unexposed face of test specimen

(b) Thermocouples at exposed face of test specimen

Fig. 8 - View of thermocouples on test specimen

3. The tests

3.1 Introduction

Table 2 gives a summary of all tests, test dates, concrete compressive strengths of the specimens at the day of testing, and the duration of the standard fire. Specimens with concrete block thicknesses of 120 mm and 200 mm were subjected to 120 minute and 180 minute standard fire test exposure [2], respectively.

Table 2 - Summary of tests

Test No.	Test Specimens	Test Date	Compressive Strength (MPa)	Duration of Standard Fire
VUT033	VUT033A	21/10/99	30.5	120 min
	VUT033B	"	"	"
VUT034	VUT034A	29/10/99	30.5	180 min
	VUT034B	"	"	"
VUT035	VUT035A	05/11/99	29.0	120 min
	VUT035B	"	"	"
VUT036	VUT036A	10/11/99	29.0	180 min
	VUT036B	"	"	"

Notes: (i) All test specimens were cast on 24/08/99.

(ii) Vertical and horizontal voids were filled on 15/09/99 and 16/09/99 respectively.

(iii) 28 day concrete cylinder compressive strength = 25.5MPa.

Fig. 9 shows an overall view of the furnace. The unexposed face of the steel plates of one of the specimens can be seen at the right-hand side of the furnace.

Fig. 9 - View of furnace during test

Non-fire-retarded PVC cabling and a piece of cardboard were attached to the thicker of the steel plates next to the unexposed face of the concrete wall. These were attached close to the end of the test for 12-13 minutes to investigate if ignition would occur.

3.2 Results

Fig.10 shows the time-temperature relationships as recorded by the air temperature thermocouples in the furnace. Alongside these points is the standard time temperature fire curve (STTC) for 180 minutes duration.

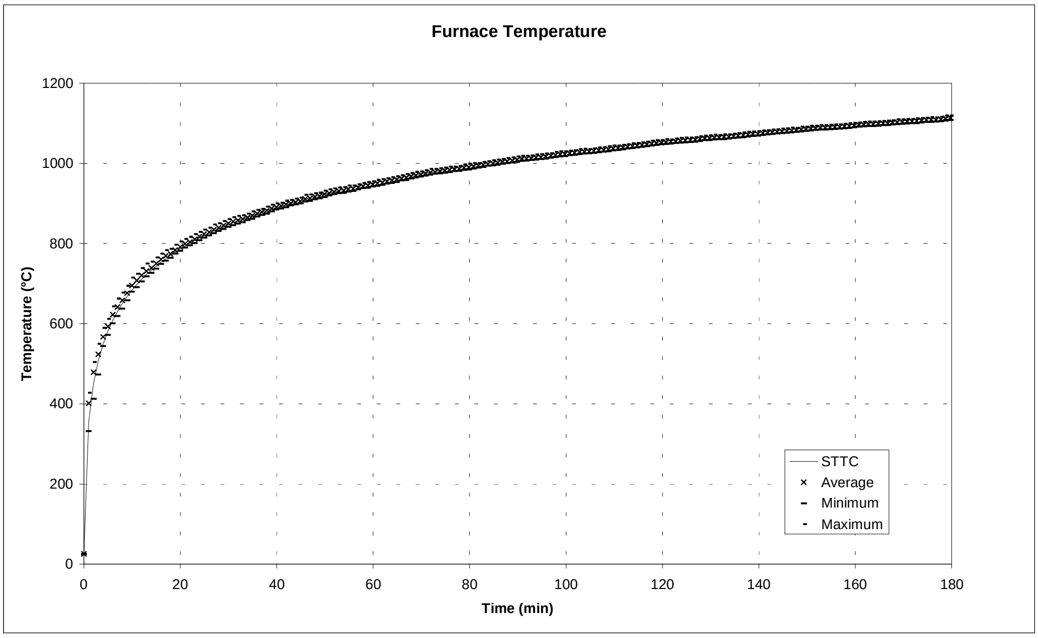


Fig. 10 - Time-temperature relationships in the furnace (Test VUT034)

Figures 11 to 14 show maximum temperatures along the length of the steel plates on the unexposed face of concrete wall. Figures 11 and 13 show snap shots of the steel temperatures at times of 60 and 120 minutes for concrete wall thickness of 120 mm. In the case of the 200 mm wall, temperatures are also given for 180 minutes, and the graphs are shown in Figs 12 and 14.

It can be seen from Figs 11 (Test VUT033) and 13 (Test VUT035) that the steel temperatures for 20 mm thick steel plate are generally less than 200°C and 280°C at times 60 and 120 minutes respectively. As for steel plate thickness of 2 mm, the maximum steel temperatures are below 95°C and 155°C at times 60 and 120 minutes respectively. The maximum temperatures and shape of the temperature distribution along the length of the steel plate suggest that the performance of the concrete is very similar irrespective of how it is cast. That is, whether the concrete was cast insitu or at a later stage, cast vertically or horizontally appears to make little difference.

Similar observations can be drawn for tests VUT034 and VUT036 which incorporated concrete wall of thickness 200 mm. From Figs 12 and 14, it can be seen that at times 60, 120 and 180 minutes, the maximum steel temperatures are generally less than 85°C, 140°C and 185°C respectively, for a steel plate of thickness 20 mm; and 45°C, 70°C and 85°C respectively, for a steel plate of thickness 2 mm.

A summary of the maximum temperatures reached for each test is given in Table 3 below. The maximum steel temperatures on the unexposed side of the concrete was recorded at the first row of thermocouples next to the face of the concrete.

Table 3 - Summary of test results

Test	Specimen	Steel plate thickness (mm)	Concrete wall thickness (mm)	Maximum temperature (°C) of steel plate on unexposed side		
				60 min	120 min	180 min
VUT033	VUT033A	20	120	193	278	-
		2	"	91	153	-
	VUT033B	20	"	181	268	-
		2	"	97	144	-
VUT034	VUT034A	20	200	80	137	179
		2	"	41	66	83
	VUT034B	20	"	81	139	183
		2	"	45	67	85
VUT035	VUT035A	20	120	182	265	-
		2	"	92	141	-
	VUT035B	20	"	176	259	-
		2	"	83	132	-
VUT036	VUT036A	20	200	79	134	170
		2	"	38	62	78
	VUT036B	20	"	80	134	171
		2	"	38	62	79

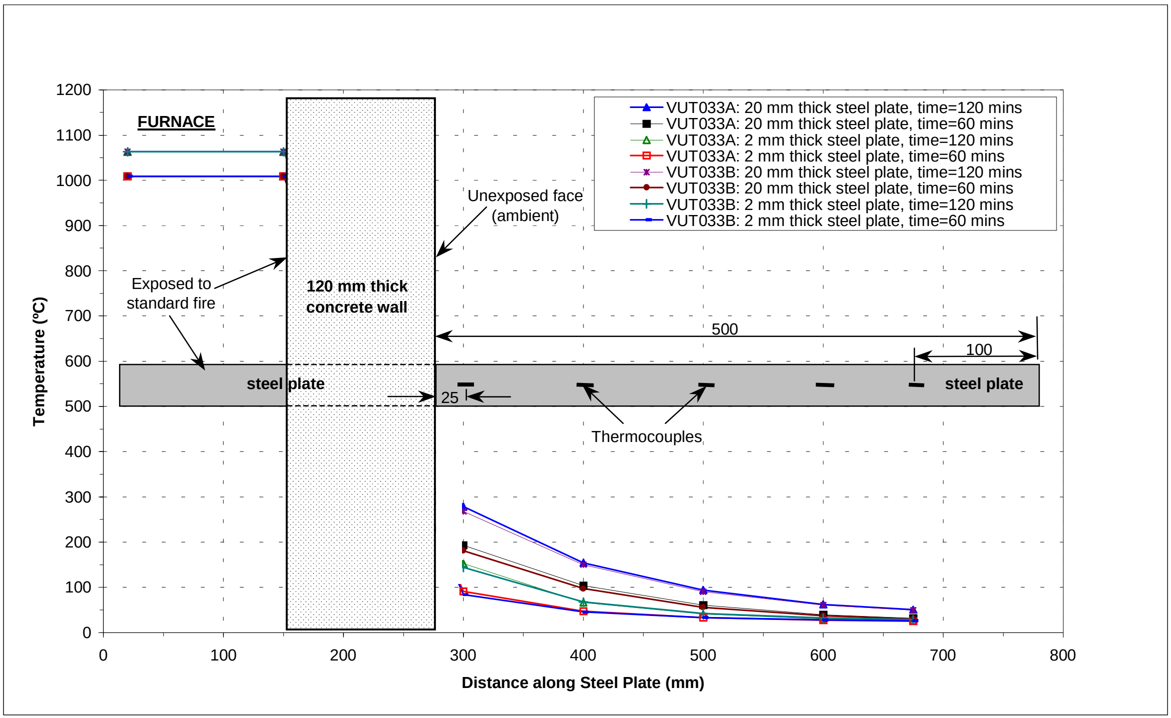


Fig. 11 - Steel plate temperatures for various exposure periods to standard fire (Test VUT033)

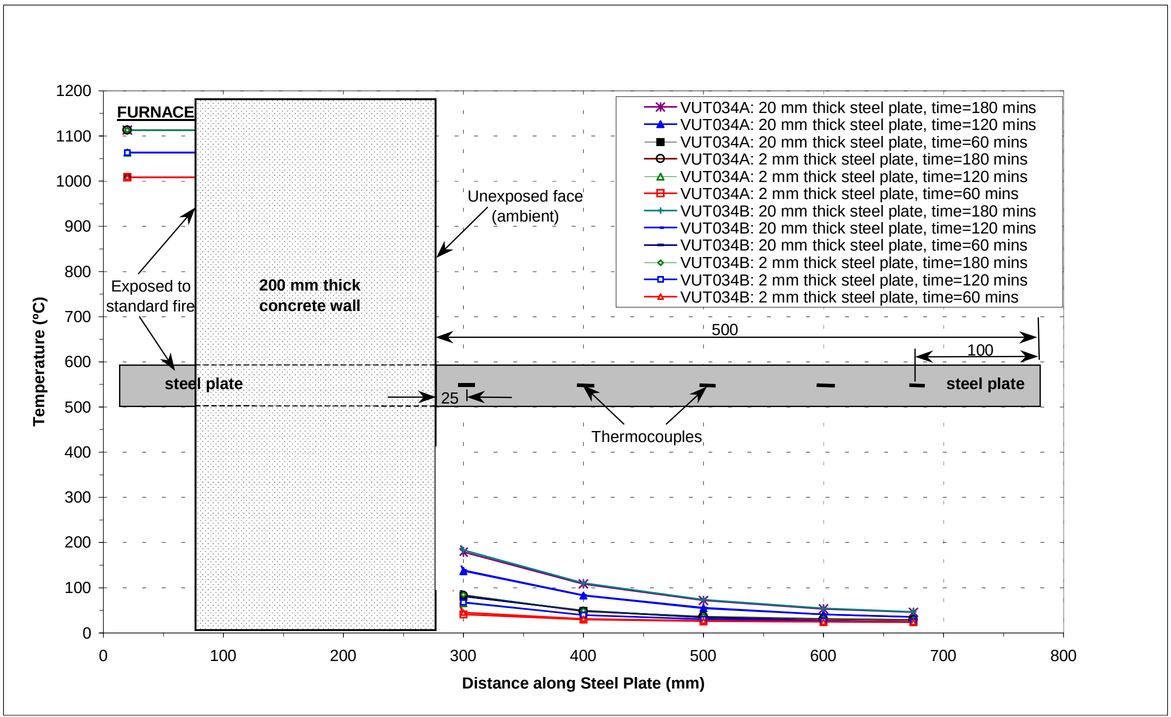


Fig. 12 - Steel plate temperatures for various exposure periods to standard fire (Test VUT034)

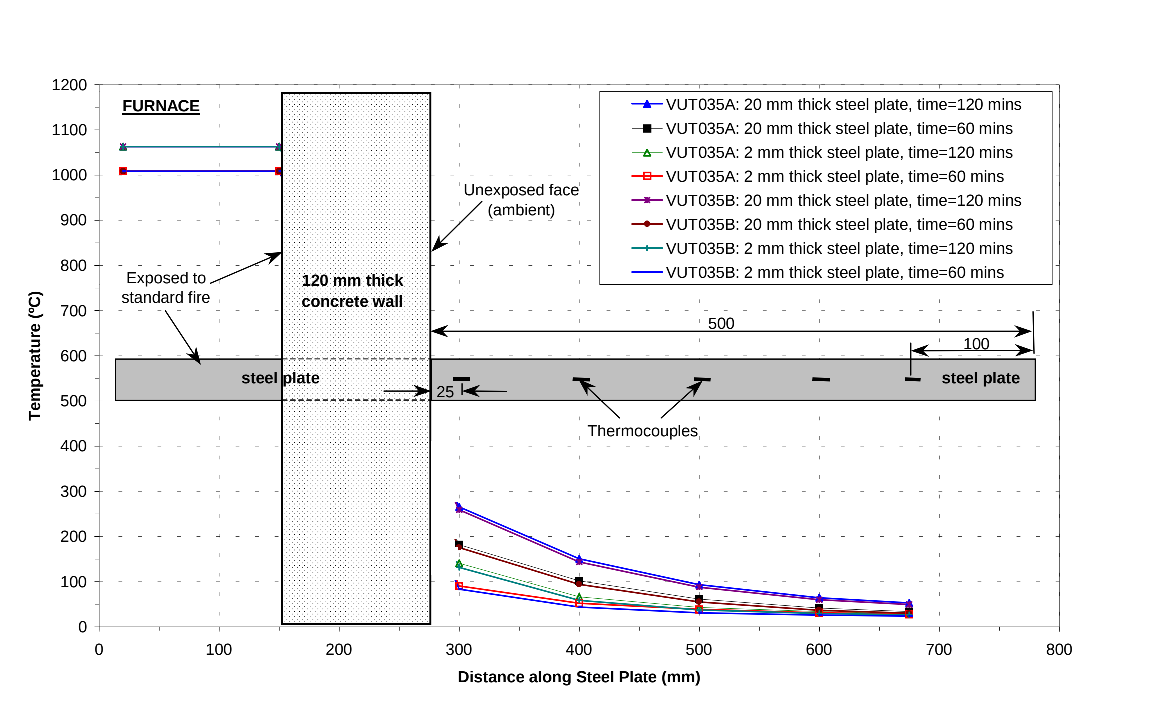


Fig. 13 - Steel plate temperatures for various exposure periods to standard fire (Test VUT035)

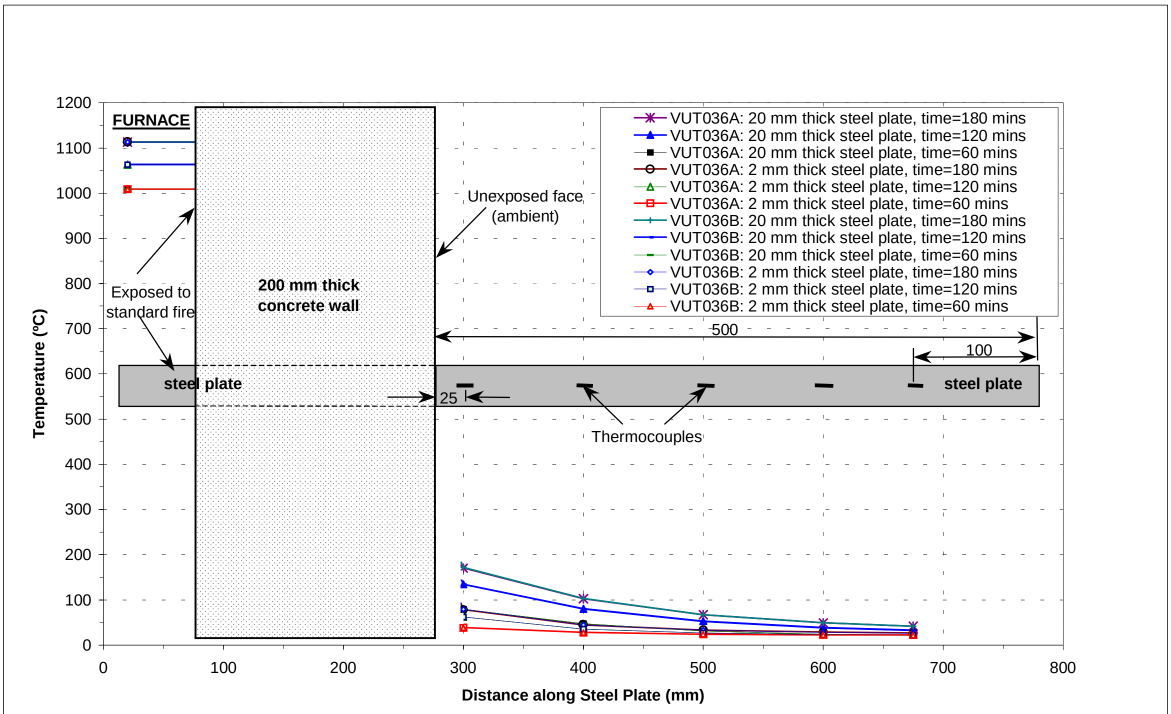


Fig. 14 - Steel plate temperatures for various exposure periods to standard fire (Test VUT036)

3.3 Observations

Figures 15 to 18 show photographs of specimens on the unexposed and exposed sides of the concrete block at the end of the tests. The steel plates directly exposed to the fire showed signs of oxidation (blistering) and the 2 mm plates have also distorted. However, this effect is not evident at all on the unexposed side.

(a) Unexposed side (b) Exposed side

Fig. 15 - Test VUT033

(a) Unexposed side (b) Exposed side

Fig. 16 - Test VUT034

(a) Unexposed side (b) Exposed side

Fig. 17 - Test VUT035

(a) Unexposed side (b) Exposed side

Fig. 18 - Test VUT036

As described earlier, non-fire-retarded PVC cables and a piece of cardboard were attached to the hottest steel plate next to the unexposed side of the concrete wall towards the end of each test (see Figs 19 and 20). In this test (VUT035), the temperatures of the steel plates near the unexposed side of the concrete wall were about 265°C and 259°C for specimens VUT035a and VUT035b respectively. After about 12-13 minutes of exposure, no ignition occurred except that the PVC cable melted and the cardboard lightly scorched, as shown in Fig. 21.

Fig. 19 - PVC cable hung from steel plate

Fig. 20 - Cardboard attached to steel plate

Fig. 21 - Conditions of PVC cable and cardboard after 12-13 minutes of exposure

3.4 Discussion

In all tests, the maximum steel temperatures recorded on the unexposed side of the test specimens were less than 280°C for concrete walls of 120 mm thick (after 120 minutes of fire exposure), and less than 185°C for walls of 200 mm thick (after 180 minutes of fire exposure). The tests also showed that regardless of the voids cast vertically, horizontally or in-situ, the maximum temperatures reached were similar. These temperatures will have little effect on the strength and stiffness of the steel member [3] and it can therefore be assumed, that on the unexposed side of the wall, the ability of the member to maintain lateral support will not be impaired. However, it is necessary for the concrete wall to be designed to resist the vertical loads imposed due to sagging of the steel member on the heated (exposed) side, as shown in Fig. 22.

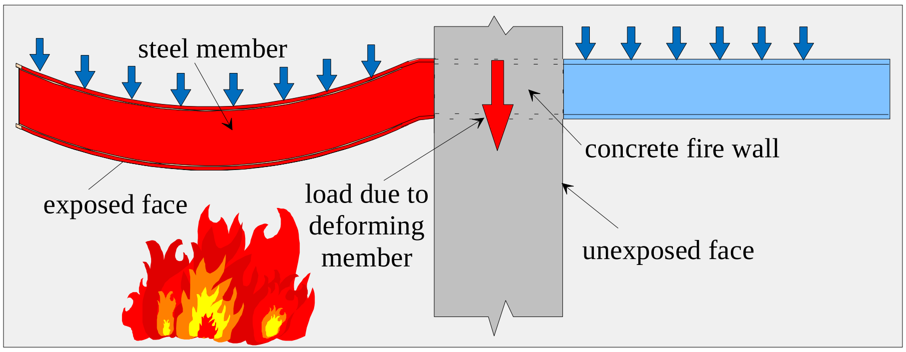


Fig. 22 - Imposed vertical load due to sagging steel member

The temperatures noted above were not sufficient to cause ignition of non-fire-retarded PVC cabling or cardboard. This is not surprising as testing conducted by Lie [4] has demonstrated that the temperatures required for ignition are much higher than the insulation failure criteria given in AS1530.4. Furthermore, experience suggests that it is very unlikely that combustibles will be stored directly in contact with the penetrating steel member at the junction of the wall. It is therefore argued that protection of a penetrating steel member is not required provided the gaps around the steel member are fire stopped to prevent the flow of hot gases and flames to the other side of the wall.

4. Conclusions

The tests reported in this paper illustrate the dramatic reduction in steel temperatures from the exposed to unexposed sides of a steel member penetrating a wall. The resulting temperatures are unlikely to reduce the stiffness and strength of the steel member on the non-fire side of the wall and are unlikely to lead to fire spread through ignition of combustible materials located on the unexposed side of the wall.

REFERENCES

1. Bennetts I.D., Culton, M., and Goh, C.C., Behaviour of Steel Members When Penetrating Fire Walls, CESARE, VUT Report No. VUT/CESARE/BHP/2000/002, March 2000.
2. Standards Australia, AS 1530.4, Methods for Fire Tests on Building Materials, Components and Structures, Part 4: Fire-resistance Tests of Elements of Building Construction, 1997.
3. Poh, K. W., Modelling Elevated Temperature Properties of Structural Steel, BHP Research Report No. BHPR/SM/R/055, September 1996.
4. Schwatz, K. J., and Lie, T. T., Investigating the Unexposed Surface Temperature Criteria of Standard ASTM E119, Fire Technology, 21, February 1985, pp. 169-180.