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Effect of Shear on Fire Response of Steel Beams

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1.0 ABSTRACT

Fire resistance of flexural members is derived based on flexural limiting criterion with no consideration to shear failure. However, under certain conditions, shear capacity can degrade at a higher rate than moment capacity in steel beams exposed to fire and this can lead to early failure of beams. This paper discusses the effect of shear on fire resistance of steel beams. For studying this phenomenon, a three-dimensional nonlinear finite element model capable of predicting fire response of steel beams is developed using the finite element package ANSYS. This model is capable of predicting fire response of steel beams under different conditions such as loading pattern, web slenderness and fire insulation. The finite element model is applied to evaluate fire response of beams with different geometrical configurations. It is shown that shear capacity can degrade at a higher rate than flexural capacity in certain scenarios and hence, shear limiting state can be a dominant failure mode in such flexural members.

Keywords: steel, fire resistance, shear capacity, flexural capacity, beams, finite element modeling

2.0 INTRODUCTION

Structural members, when exposed to fire, experience loss of capacity and stiffness due to temperature induced degradation in strength and modulus properties of constituent materials. When the capacity at the critical section of a beam drops below the applied moment due to loading

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failure occurs in the member. The time to reach this failure is referred to as fire resistance. In current practice, failure in beams under fire conditions is evaluated based on flexural limit state without any consideration to shear capacity. This is in contrast to ambient temperature design, where a beam is generally designed to satisfy flexural limits state and then checked for shear resistance. Deriving failure in fire exposed beams based on flexural limit state, although valid for most common scenarios, may not be representative in certain situations where shear forces are dominant or shear capacity degrades at a rapid pace with fire exposure time. Also, in the case of beams with slender webs, shear capacity degrades at a much rapid pace than flexural capacity due to local buckling occurring in webs resulting from rapid rise in temperatures in webs.

Shear forces can be dominant in beams under certain loading configurations such as high concentrated (point) loads acting on the beam, as in the case of transfer girders. The most common example arises from concentrated loads near end of beams connecting to offset columns in buildings [2]. Another case where shear can control the design is in beams with reduced cross-sectional area (coped beams). Coped beams are usually used at beam-to-column joint connections. Moreover, short span beams subjected to high loads can fail due to shear rather than flexural effects. Further, in beams with slender webs, such as deep beams and plate girders, reserve shear capacity can be much lower at ambient conditions and under certain situations shear effects can trigger failure in fire exposed deep beams.

A review of literature clearly show that most previous studies focused on fire behavior of beams where bending effects dominate response [1-4]. These studies considered effects of various factors on flexural response of steel beams such as restraint conditions, inelastic response, thermal

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gradients etc. Unfortunately, the effect of shear forces capacity was not considered in evaluating fire response beams. In one notable study, Dharma and Tan [1] have developed a finite element model to evaluate inelastic rotational behavior of steel beams subjected to fire conditions. They applied this model to study the effect of web and flange slenderness on fire response of steel beams. The authors reported a noticeable decrease in flexural and shear capacity with increase in flange and web slenderness. In addition, they reported that moment capacity of fire exposed steel beams decreases significantly in beams with slender webs due to occurrence of local buckling in webs. However, no specific observations were made with regard to the influence of web slenderness on shear capacity in fire exposed beams.

To evaluate effect of shear on response of a fire exposed beam, a numerical study is carried out using a three-dimensional nonlinear finite element model. This model can trace the fire response of hot-rolled or built-in W-shaped beams subjected to significant bending moment and shear force. This model is applied to examine the influence of shear on fire response of beams under different loading configurations, web slenderness and fire insulation parameters.

3.0 RESPONSE OF STEEL BEAMS TO FIRE

In conventional design, beams are subjected to significant levels of bending moment and thus failure typically occurs when the applied moment due to loading at the critical section exceeds the moment capacity. Therefore, under ambient conditions, beams are typically designed to satisfy flexural limit state and then checked for shear limiting criteria. However, when exposed to fire, beams experience significant loss of moment and shear capacity with fire exposure time. In current practice, failure in fire exposed beams is evaluated by considering flexural strength limit state with

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no consideration to shear limit state or local buckling limits. Although such rationale can be valid for most common scenarios in buildings, it may not be valid in certain situations such as the case of transfer girders or beams with slender webs.

Transfer girders used where large free space is needed, i.e. in lobbies and conference halls, can be subjected to high shear forces; resulting from concentrated loads arising from supporting columns or walls. Further, webs in W-shape sections or plate girders are usually thinner (slender) than flanges. These webs can be exposed to higher thermal (fire) loading; since they are exposed to the fire from two sides (larger surface area). Hence, strength properties of steel in the web can degrade at a higher rate than that in flanges. Once exposed to high temperatures, shear capacity of steel beams can degrade at a much higher rate than flexural capacity since area of the web is main contributor to shear capacity.

These situations, wherein shear limits state can dominate, are illustrated by tracing response of a typical steel beam from loading stage to failure under fire exposure. Figure 1 shows a simply supported beam subjected to two different loading scenarios. The moment and shear capacity of the beam at ambient conditions and after 2 hours of fire exposure is plotted in Fig. 1. In the case of a beam subjected to uniformly distributed loading (UDL), typically failure occurs when the applied bending moment exceeds the moment capacity at the mid-span section as shown in Fig. 1a. Even under fire conditions, flexural effects govern the failure in this beam and; the beam fails when degrading moment capacity at critical section (mid-span) falls below that of applied bending moment. This is mainly due to the fact that the beam has high shear resistance (higher than applied shear force) even at 2 hours of fire exposure.

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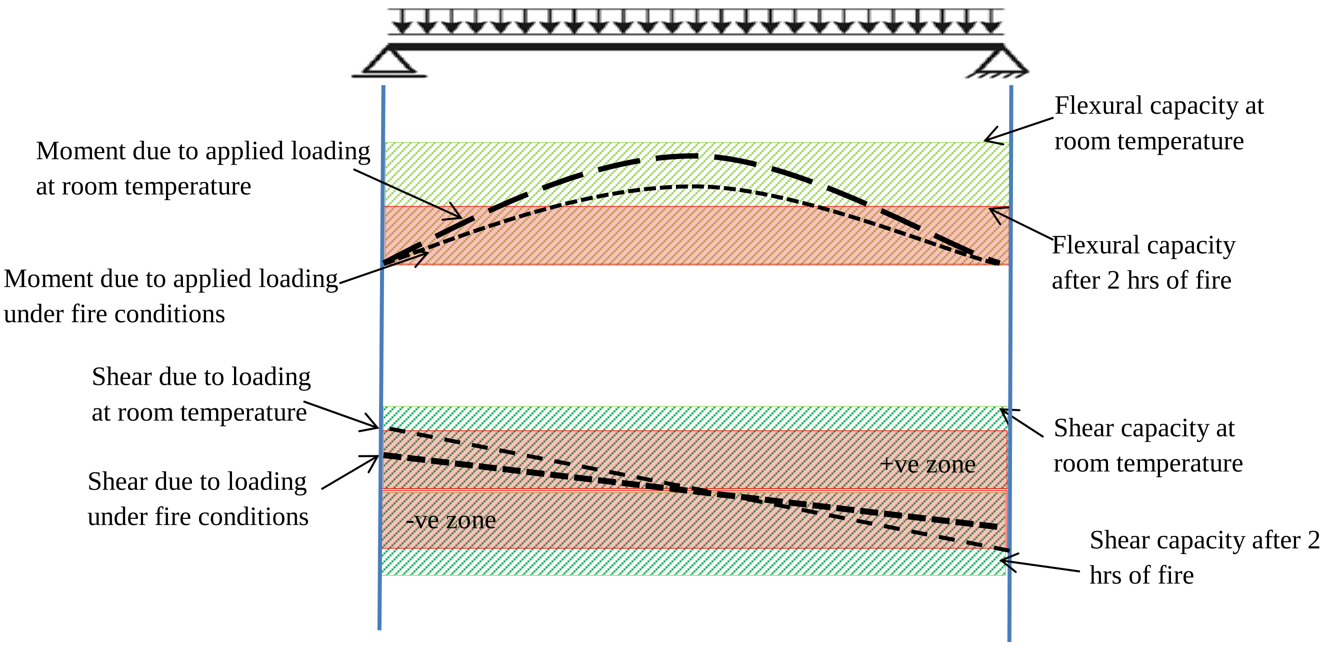
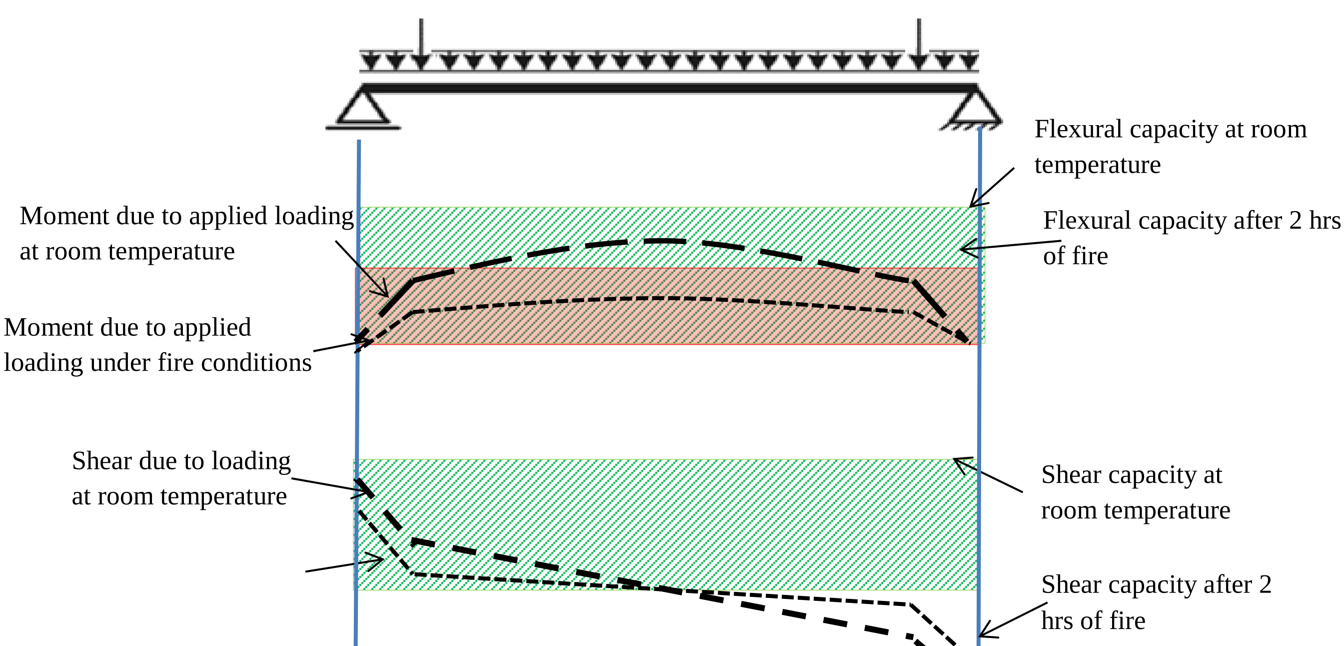
On the other hand, Fig. 1b shows the same beam but subjected to point loads. This beam is subjected to significant level of shear forces (compared to flexural forces). Thus under fire conditions failure occurs due to shear capacity dropping below the applied shear force prior to onset of flexural limit state as shown in Fig. 1b. Since the beam has sufficient reserve moment capacity, the beam attains shear failure when the rapidly degrading shear capacity exceeds shear force at the critical section.



(a) Beam with uniformly distributed loading at ambient and fire conditions



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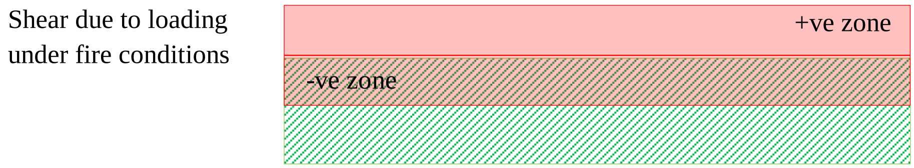

(b) Beam with high shear forces at ambient and fire conditions

Fig. 1. Variation of bending moment and shear force under different loading scenarios

(Capacity at room temperature, Capacity under fire conditions)
(Shear/moment loading at room temperature, Shear/moment loading under fire conditions)

4.0 NUMERICAL MODEL

To study the effect of shear on the response of beams under fire conditions, a finite element model was developed using ANSYS 14.0. For tracing the realistic fire response of beams, several parameters such as geometric and material nonlinearities, temperature dependent material properties and various failure limit states are accounted for in the analysis. The main features of the model, including discretization, material properties and various failure limit states, are discussed below.

4.1 Geometry and discretization

The three dimensional finite element model has geometry of a typical hot-rolled built-in steel I-section commonly used in flexural members. In order to model the transient thermal-stress analysis, different thermal and structural element types available in ANSYS 14.0 are used. SOLID70 and SURF152 elements are used as thermal elements to simulate heat transfer under fire conditions. SOLID70 is a thermal element with conduction capability, while, SURF152 is a four-noded thermal element capable of simulating heat conduction, convection and radiation. Typically,

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SURF152 is overlaid on top of SOLID70 elements to simulate convection and radiation effects from fire zone to structural member. SOLID185 which has eight nodes is used for modeling three-dimensional solid structure. This cubic element has three degrees of freedom at each node: translations in the nodal x, y, and z directions and it can account for large deflections, and large strain effects [6].

Upon successfully completing thermal analysis, SOLID70 thermal elements are transformed into SOLID 185 structural elements. Such transformation is necessary to account for degradation of mechanical properties of constituent materials at elevated temperatures for structural response predictions. The finite element model is meshed using equal side quadrilateral-type mesh to ensure uniformity. A typical beam has an average of 35,000 elements. An isometric view of the developed finite element model is shown in Fig. 2.

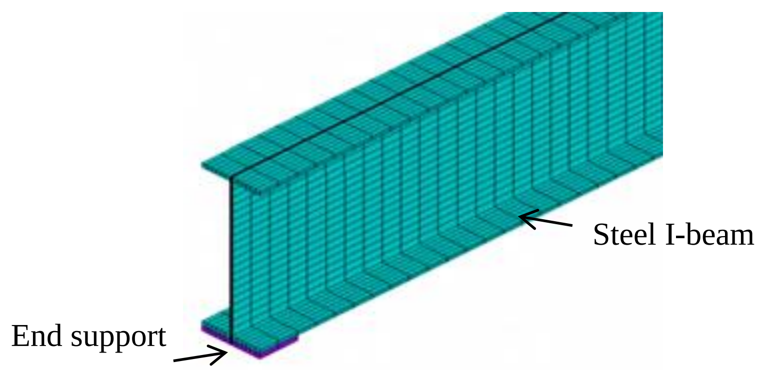

Fig. 2. Isometric view of the finite element model

<u>4.2 High temperature material properties and constitutive laws</u>

For undertaking fire resistance analysis, temperature-dependent thermal and mechanical properties of steel and fire insulation are to be input to the finite element model. Thermal properties comprise of density, specific heat and thermal conductivity, while, mechanical properties include

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yield strength, modulus of elasticity, stress-strain relationships and coefficient of thermal expansion. Thermal and mechanical properties of structural steel are assumed to vary with temperature as per Eurocode 3 recommended relations [7]. The nonlinearity in steel material is accounted for through a bi-linear elasto-plastic constitutive material model based on the Von-Mises plasticity yielding criterion. For fire insulation, room temperature thermal properties are used in fire resistance analysis since there is very limited information on high temperature thermal properties.

4.3 Failure Criteria

In the analysis, different limiting criteria namely flexural, shear and deflection limit states are considered for evaluating failure of the beam at each time step. Flexural and shear failure occur once the bending moment (or shear force) due to applied loading exceed the moment (or shear) capacity at a critical section. In addition, deflection limit state is also applied to evaluate failure at each time step. Accordingly, when the beam attains a deflection of ($L/20$) or rate of deflection reaches ($L^2/9000d$); where L and d are the span and depth of the beam, respectively, the beam is said to fail [8, 9].

5.0 MODEL VALIDATION

Since there is lack of published experimental data on steel beams subjected to high shear forces, the above finite element model was validated using data from tests on conventional steel beams. Kodur and Fike [10] have conducted fire resistance test on a 4 m long W12×16 A992 steel beam under ASTM E119 standard fire. The beam was insulated with 50 mm thick spray applied vermiculite based fire insulation to achieve a 2-hr fire resistance rating. Fig. 3 shows layout of the tested beam. The beam was loaded with two point loads and this loading represented 31% of its flexural capacity at room temperature. The moment and shear capacity of the beam is at room temperature 102.2 kN.m and 440 kN, respectively.

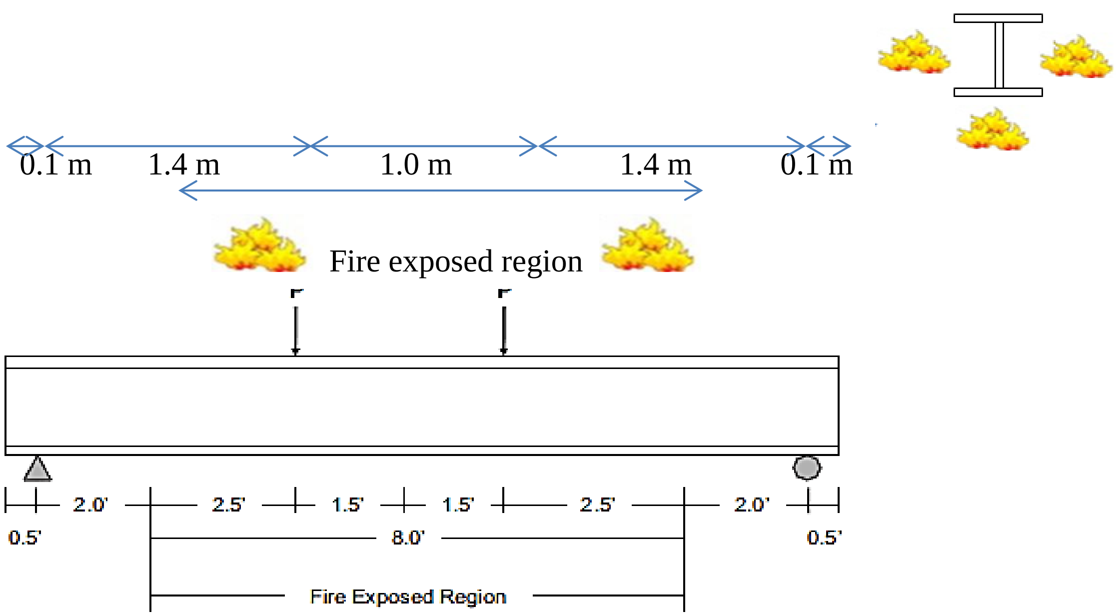
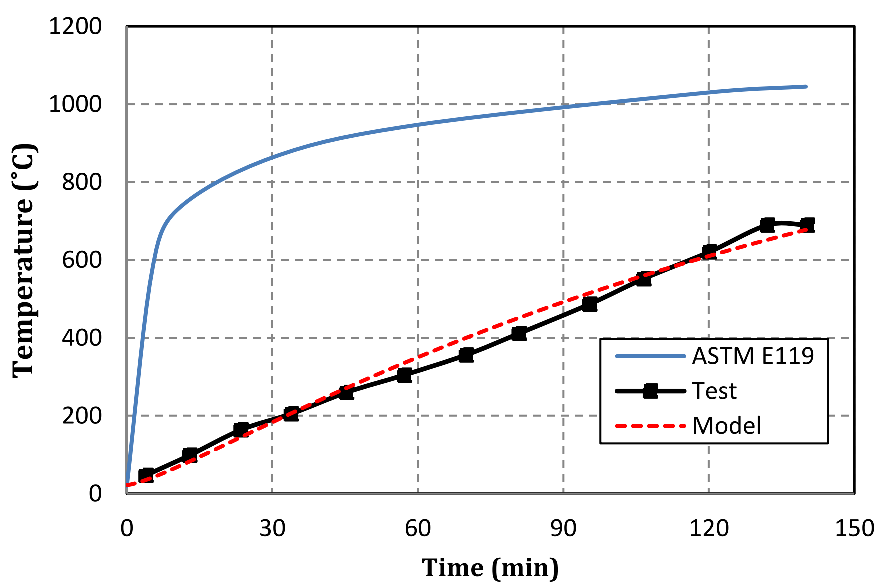


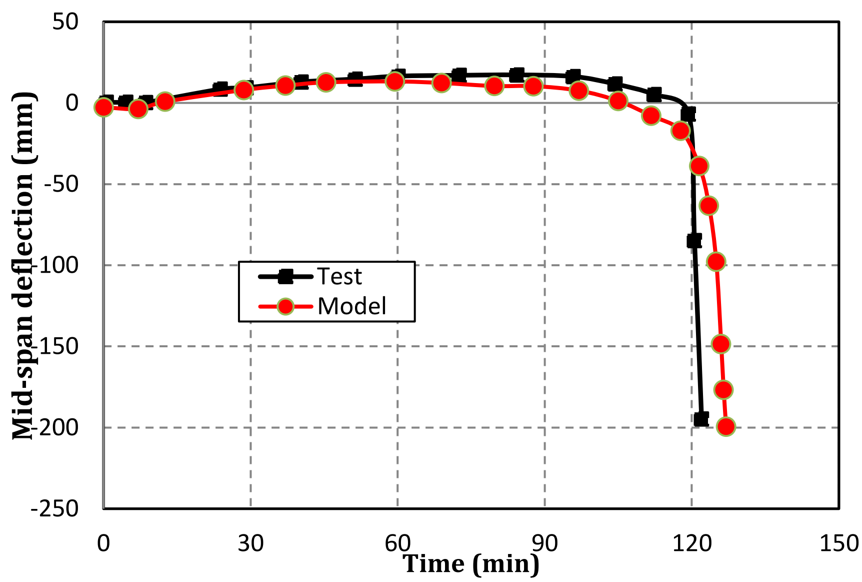
Fig. 3. Tested beam used in validating the developed finite element model

The tested beam is analyzed using the above developed model and various output parameters generated in the analysis, namely temperatures, mid-span deflection and failure mode are compared against measured data from tests. Figure 4 shows a comparison of predicted and measured temperatures in the steel beam as a function of fire exposure time. In general, temperatures in steel section rise steadily but slowly due to the presence of fire insulation. These plotted temperature in the steel section is the average of top and bottom flange and web temperature. It can be seen that there is a good agreement between predicted and measured temperatures up to first 45 minutes (till 350˚C) in steel). Then, the predicted temperatures tend to be slightly higher than the measured ones; such variation can be attributed to differences in assumed and actual thermal properties of fire insulation at elevated temperatures. However, both measured and predicted temperatures converged toward the end of fire exposure.

A comparison of predicted and measured mid-span deflection response of the tested steel beam is shown in Fig. 4b. The beam undergoes only small deflection and this remains constant in the first 90 min. This can be attributed to low temperature in the beam facilitated by the presence of fire insulation. Steel does not experience significant degradation in strength and modulus properties when the temperature is below 400˚C, hence deflections remains small. However, as the temperature in steel beam reaches 550˚C, at about 100 min, strength and stiffness properties of steel start to degrade at a faster rate leading to rapid rise in deflection. Finally, after two hours of fire exposure, steel loses most of its strength and stiffness as the temperature of the beam rise to 600˚C. This leads in rapid rise in mid-span deflection and produces runaway failure in the beam at 122 min.



(a) Thermal response



(b) Structural response

Fig. 4. Comparison of predicted and measured temperature and deflections as a function of fire exposure time

The applied loading on this beam is low and thus the resulting levels of bending moment at mid-span and shear force at mid-span and support sections is 31 and 5% of moment and shear capacity, respectively. Figure 5 shows the degradation of moment and shear capacity with fire exposure time at corresponding critical sections; mid-span section for moment and support section for shear. The moment capacity in the beam remains intact for the first 75 minutes due to lower temperatures (much below 350˚C) in flanges of steel beam. However, shear capacity starts to degrade at 35 min due to relatively faster rise in web temperature. Then, moment and shear capacity starts to degrade when the temperature in steel section exceeds 350˚C. Degradation of moment capacity of steel section continues till 130 min at which point the beam fails since the capacity at mid-span falls below the moment due to applied loading. However, due to the low level of applied shear force, shear capacity does not fall below the shear force near the vicinity of support

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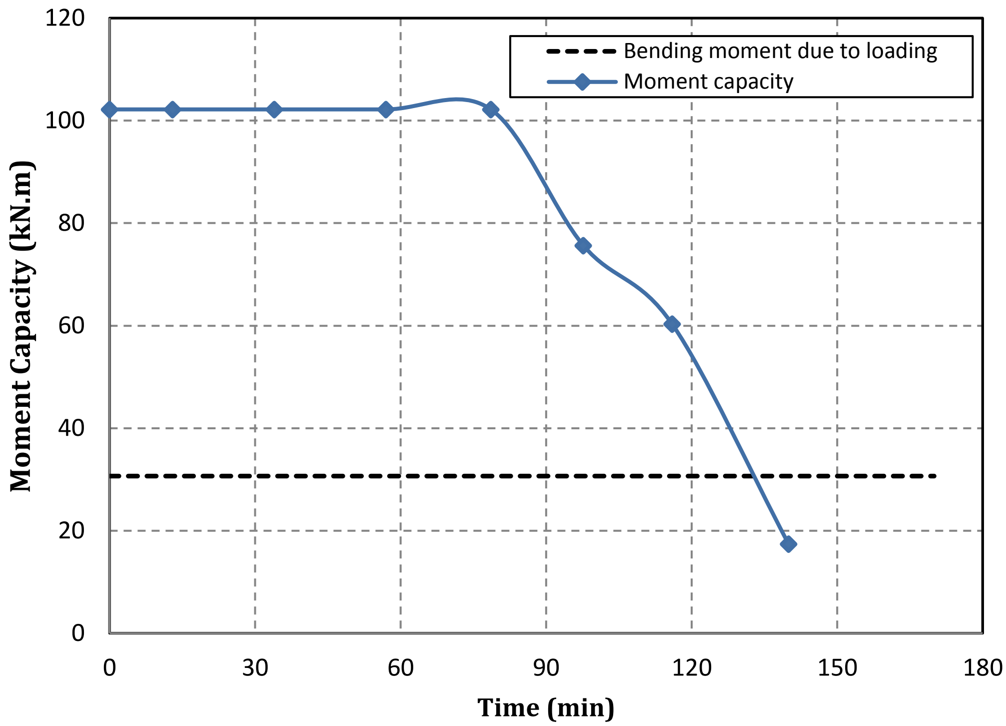
section. Hence, failure of this beam occur due to flexural effects at 130 min (failure of this beam in fire test occurred at 122 min).



(a) Moment capacity

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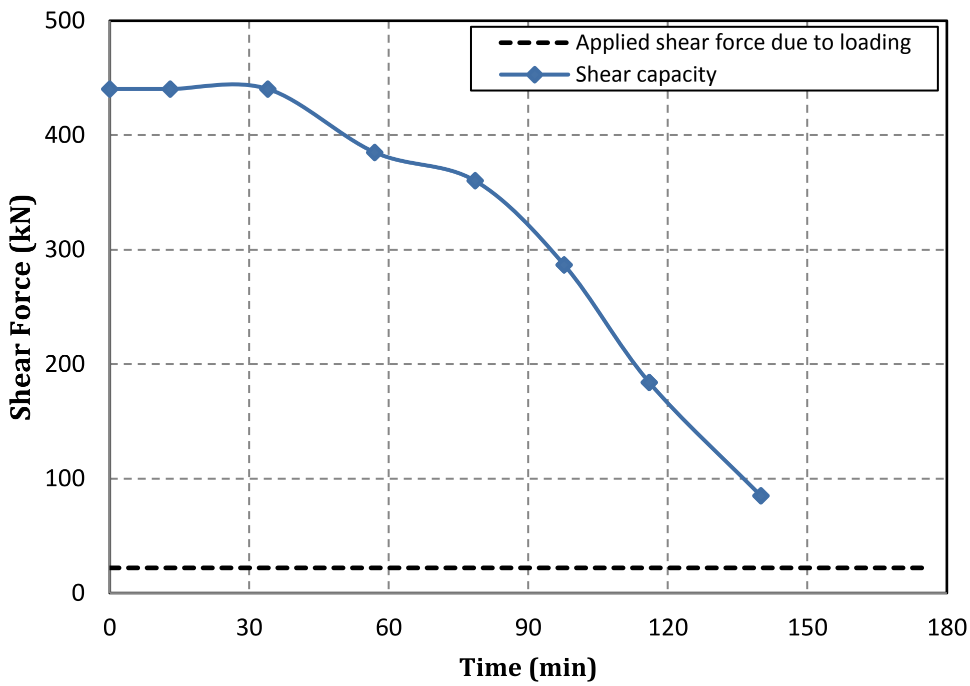

(b) Shear capacity

Fig. 5. Degradation of moment and shear capacity in the tested beam [10]

6.0 CASE STUDIES

The above validated finite element model was applied to study the effect of shear parameters dominating fire response in steel beams. The effect of loading pattern, web slenderness and fire insulation on shear force (and capacity) and thus on fire response of beams is studied.

6.1 Effect of loading pattern

For the analysis, a simply supported beam of W16×31 section (from AISC design manual [11]) with a flange width of 140.6 mm and overall depth of 404 mm is selected. The flange and web thicknesses are 11.2 mm and 7 mm, respectively. The beam is made of Grade 345 (MPa) steel and has continuous lateral support provided along its 9.14 m span. To illustrate the effect of shear

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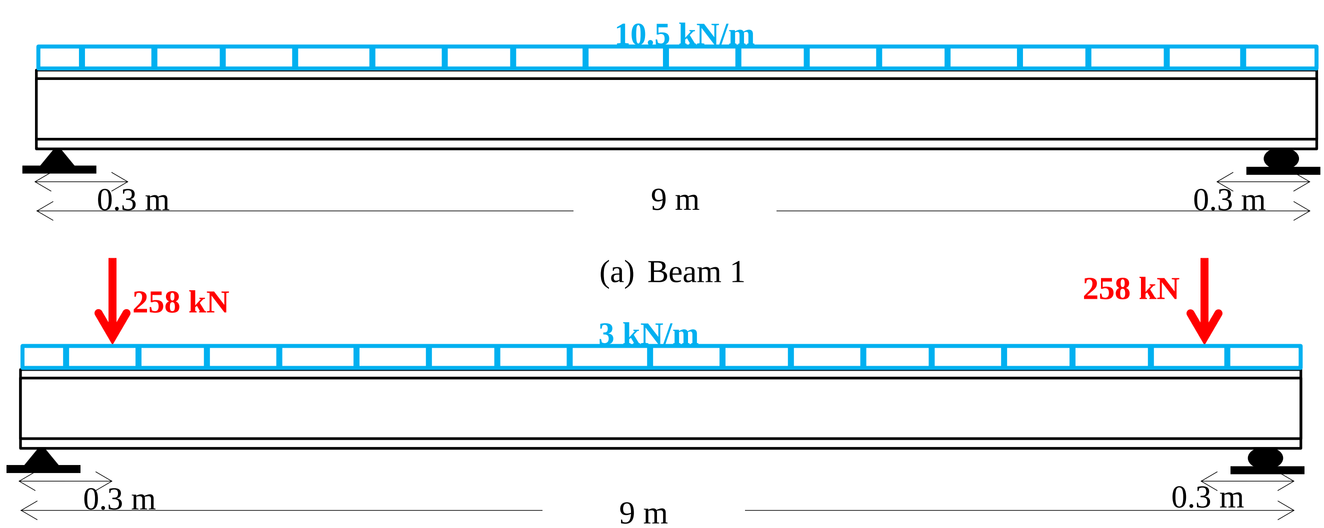
arising from different loading patterns, three configurations of this beam, “Beam 1”, “Beam 2” and “Beam 3” were analyzed.

“Beam 1” is subjected to uniformly distributed loading (UDL) of 10.5 kN/m. “Beam 2” is subjected to UDL (3 kN/m) together with two concentrated loads of 258 kN applied close to the supports. “Beam 3” is subjected to a UDL of 3 kN/m together with two concentrated loads of 40 kN applied at 1.8 m away from end supports. The selected loading in these three beams generate same magnitude of peak bending moment, at the critical mid-span section, however resulting shear force distribution along the beam would be different. It should be noted that these selected load levels represent about 50% of flexural and shear capacity at room temperature, which is similar to load levels encountered during fire conditions). Figure 6 shows a layout of the four point bending set-up. The beams were designed as per AISC provisions [11] and have a flexural capacity of 275 kN-m and shear capacity of 584 kN at room temperature. It should be noted that the loading of “Beam 2” was chosen to simulate a pure shearing state and this loading set-up is similar to the one used by Basler et al. [12] to study shear response of steel beams at room temperature.



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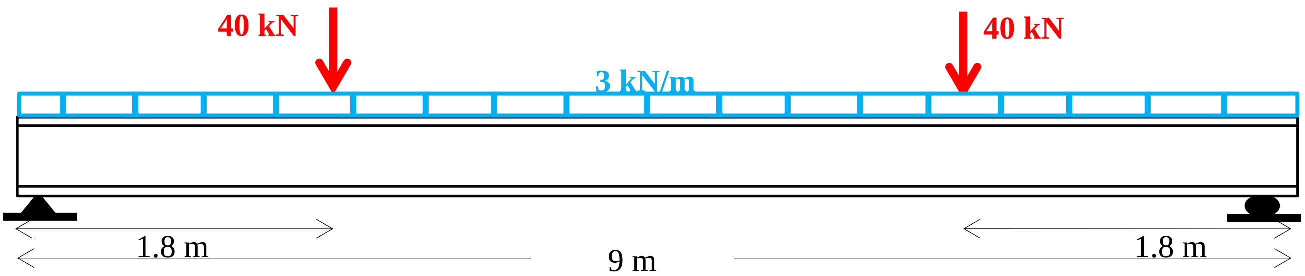
(b) Beam 2



(c) Beam 3

Fig. 6. Loading on beams used in case study

The above three beams were analyzed by subjecting them to aforementioned loading while simultaneously exposing them to ASTM E119 standard fire curve. Figure 7 shows temperature progression in the three beams with fire exposure times. Since these three steel beams have same geometric and material properties and subjected to similar thermal loading, temperature rise in all three beams is identical. It can be seen from Fig. 7 that steel temperature in web and bottom flange increases at a higher rate with fire exposure time as compared to that in top flange. Temperature in the web reaches 500˚C at 10 min into fire exposure and further reaches 760˚C at 20 minutes.

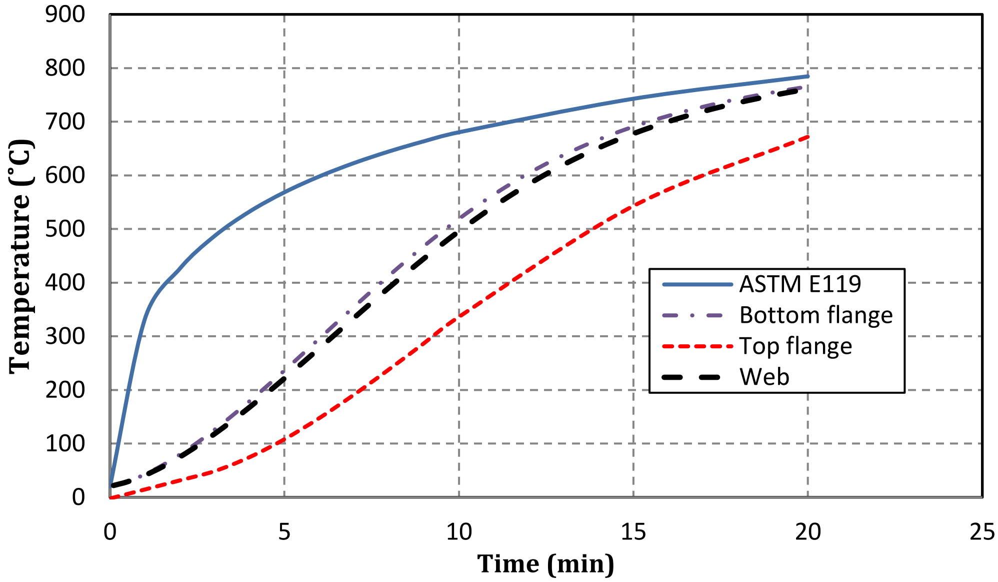


Fig. 7. Temperature in steel beams 1, 2 and 3 as a function of fire exposure time

Figure 8 shows the degradation of moment and shear capacity of the analyzed steel beams under fire exposure along with bending moment and shear force generated from applied loading. These plotted moment and shear capacities are at critical sections namely, mid-span for moment and location of point loading for shear force. As expected, moment and shear capacity in steel beams starts to degrade after 9 minutes into fire exposure. This is due to temperature in lower flange and web exceeding 400˚C as shown in Fig. 7. As the temperature rise continues, further degradation of moment and shear capacity takes place until failure of beams.

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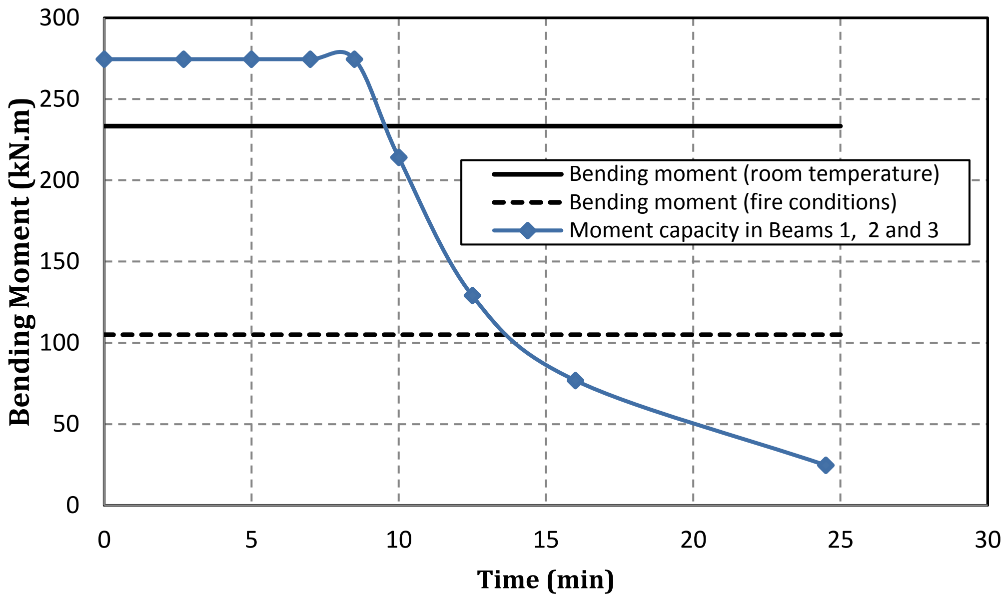
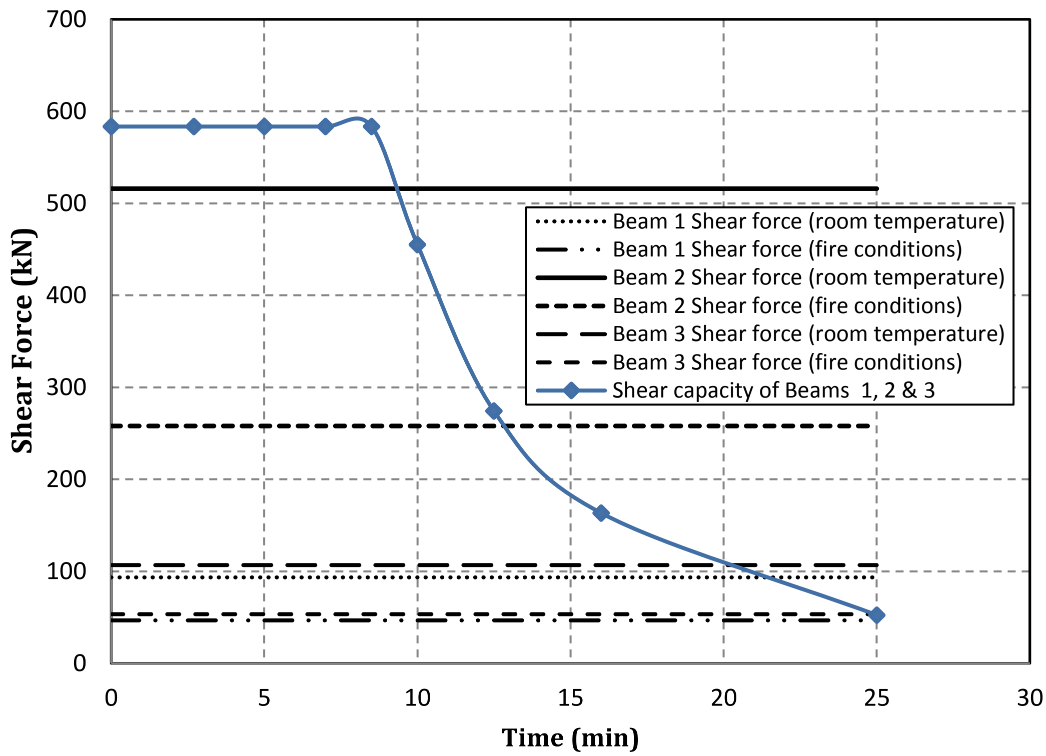


(a) Moment capacity



(b) Shear capacity

Fig. 8. Degradation of bending moment and shear capacity with fire exposure time

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Figure 9 shows the predicted mid-span deflection in these three beams as a function of fire exposure time. The mid-span deflections are very small for about 13, 6 and 9 min in Beams 1, 2 and 3, respectively. Then, deflections increase at a rapid pace prior to failure of these beams.

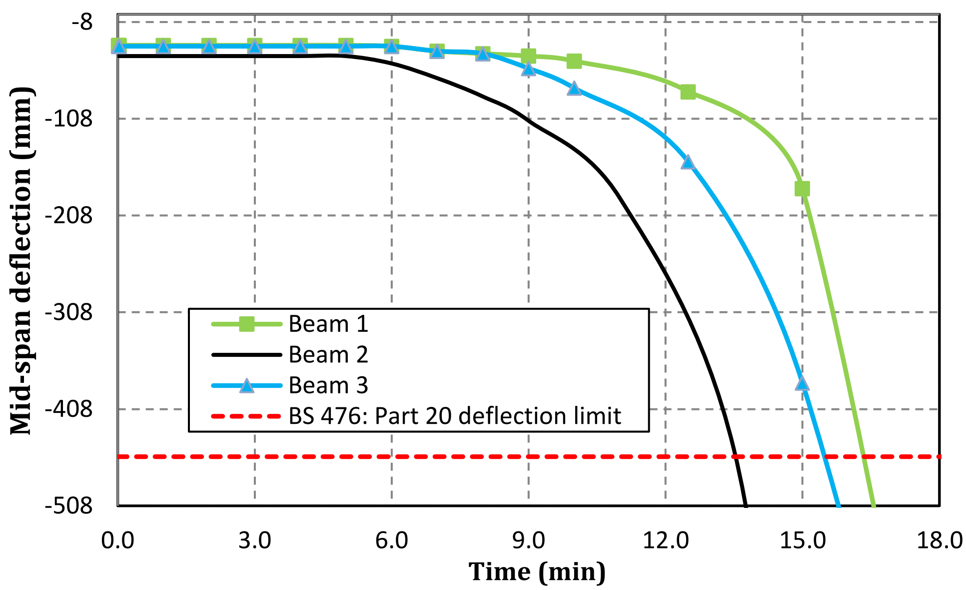

Fig. 9. Variation of mid-span deflection with fire exposure time in “Beam 1”, “Beam 2” and “Beam 3”

The above generated results were utilized to evaluate failure of beams under different limit states. Failure of the beam is said to occur when moment (or shear) capacity drops below applied bending moment (or shear force) or when mid-span deflection exceeds limiting deflection criterion. It is clear from Fig. 8 that “Beam 1” attains failure in flexural mode at about 14 min when the moment capacity drops below the applied moment due to loading (UDL). On the other hand, “Beam 2” would fail through shear limiting state at 13 min, prior to onset flexural limiting state. Further, “Beam 3” experiences failure in flexural mode at 14 min.

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It can be seen from Fig. 9 that runaway (large deflection) failure starts around 10, 6 and 8 min in Beams 1, 2 and 3, respectively, due to significant degradation of stiffness resulting from temperatures in steel exceeding 550˚C. As discussed above, British Standard (BS-476) recommends a deflection limit of (*L/20*) for deflection failure. If the deflection limit recommended by the British Standard [9]; ($\frac{L}{20} = 457mm$) is applied, occurs at 17, 13.8 and 15.1 min in Beams 1, 2 and 3.

While Beams 1 and 3 fails in flexural mode, "Beam 2" fails in shear limit state earlier to reaching deflection or flexural capacity limit states. Table 1 summarizes failure time in these beams. These results infer that a fire exposed beam under certain loading scenarios can fail through shear limiting state prior to attaining flexural or deflection limiting states. Although the applied loading on these three beams resulted in similar bending moment, different loading pattern led to different failure modes (and fire resistance). Thus, loading pattern can significantly affect the fire response of steel beams. It should be noted that there is only slight difference in failure time of these uninsulated beams. However, effect of different failure limit states and corresponding failure times can be more apparent in insulated beams as will be discussed in subsequent section.

Table 1 Failure time of Beams 1, 2 and 3

Beam	Loading	Failure time (min)			Failure mode
		Shear	Flexure	Deflection	
Beam 1	Uniformly distributed loading (UDL)	25	**14**	17	Flexure
Beam 2	Concentrated loading near supports + UDL	**13**	14	13.8	Shear

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Beam 3	Concentrated loading near mid-span + UDL	24	**14**	15.1	Flexure

6.2 Effect of web slenderness

In typical steel beams, flanges mainly contribute to moment capacity, while web contributes to shear capacity. Thus, sectional slenderness of web has significant influence on shear capacity of the beam. Typically, for optimum design, slenderness of web is much higher than that of flanges and hence web slenderness is a critical factor in determining shear capacity in a steel beam. The effect of web slenderness on shear capacity is studied by analyzing three fire exposed beams with varying web slenderness. Two of these beams, "Beam 4" and "Beam 5" are replicates of "Beam 2" shown above, but with different web thicknesses. Table 2 lists web slenderness and limiting web slenderness ratios for evaluating shear capacity at ambient conditions [11]. These three beams (Beams 2, 4 and 5) were analyzed with the above developed model and based on predicted response; failure of the beams is evaluated under different limit states. It should be noted that Beams 4 and 5 were subjected to loading corresponding to about 50% of flexural and shear capacity at room temperature, which is similar to load level encountered during fire exposure conditions.

Table 2 Beams with different slenderness ratios

Beam	Web thickness (mm)	Web slenderness ratio (λ_w)	Slenderness limits		
			$2.24\sqrt{\frac{E}{f_y}}$	$1.10\sqrt{\frac{k_v E}{f_y}}$	$1.37\sqrt{\frac{k_v E}{f_y}}$
Beam 2	7	57.82	63.58	69.81	86.95
Beam 4	5	75.10			
Beam 5	3.8	100.13			

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The slenderness ratio of web and flanges for this "Beam 2", classified as compact section, are λ_w $(h/t_w = 57.82)$ and λ_f $(b_f/2t_f = 6.28)$, respectively; where h, t_w, b_f and t_f are web height, web thickness, flange width and flange thickness, respectively. To illustrate the effect of web slenderness on temperature rise, predicted temperature in the web of three beams are plotted in Fig. 10 as a function of fire exposure time. The overall thermal response in Beams 4 and 5 follow similar trend to that of "Beam 2"; however, the temperature in webs of Beams 4 and 5 increases at a much faster pace due to slender webs. Thus, faster degradation of strength and stiffness properties occurs in "Beam 4" and "Beam 5" as compared to that in "Beam 2".

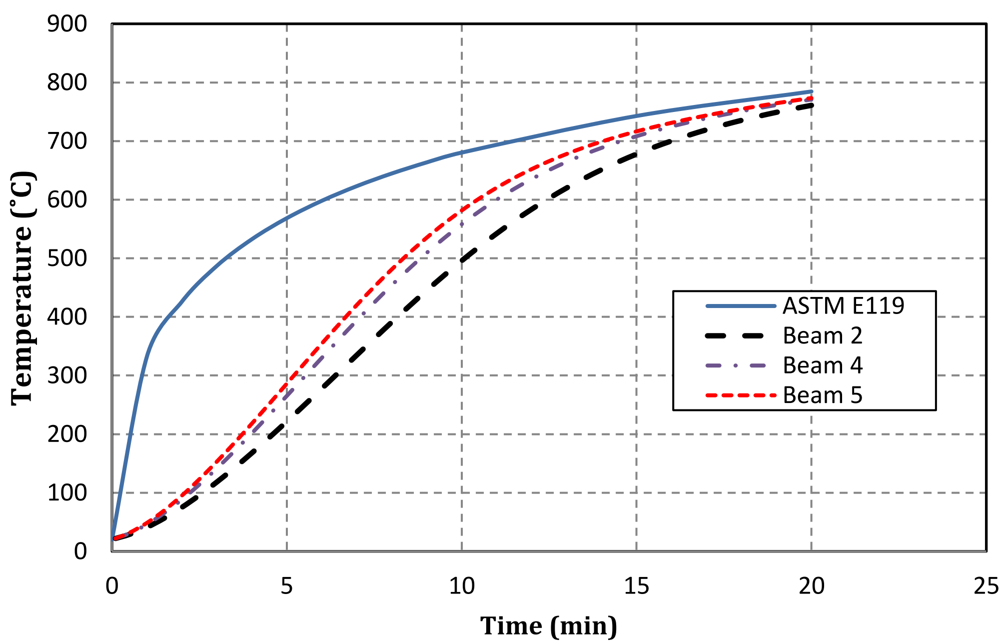

Fig. 10. Variation of temperature in web of Beams 2, 4 and 5 with fire exposure time

Figure 11a shows degradation of moment capacity with fire exposure time at the mid-span section of Beams 2, 4 and 5. It should be noted that moment capacity at ambient conditions in these three beams are slightly different resulting from reduced web thickness; thus reduced plastic modulus. Figure 11b shows degradation of shear capacity as a function of fire exposure time. Since

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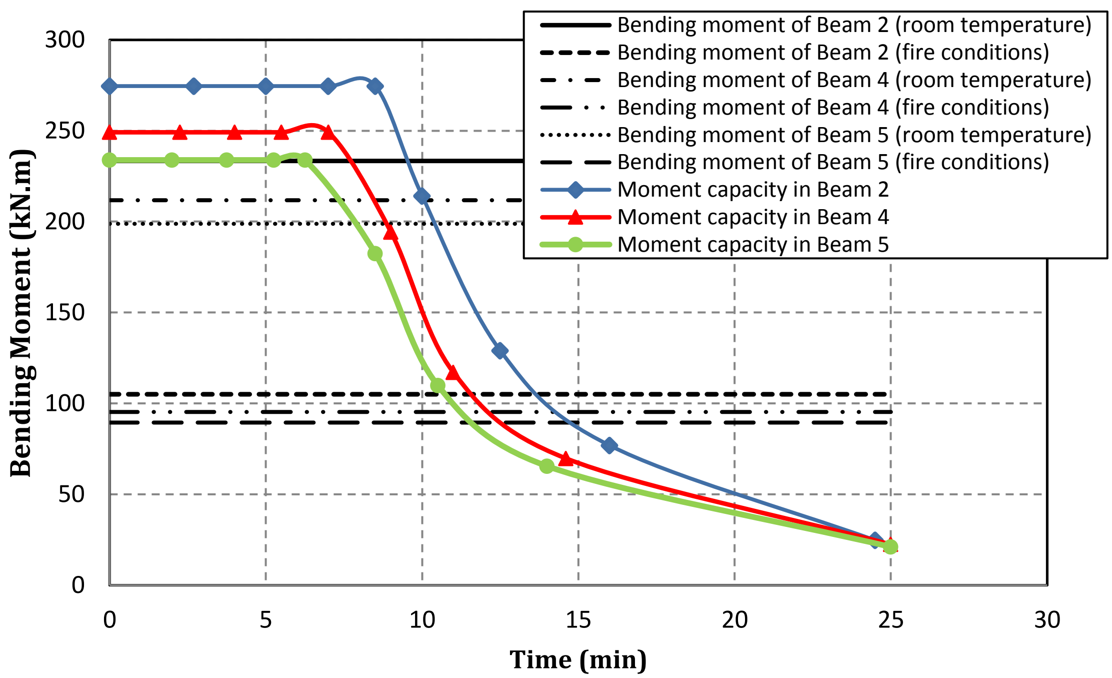
shear capacity is mainly governed by the size of the web, shear capacity of Beams 4 and 5 at ambient conditions is much lower than that of "Beam 2" due to large reduction in web thicknesses. In addition, shear capacity in fire exposed "Beam 4" and "Beam 5" degrade at a higher pace than that in "Beam 2" due to faster rise in web temperature resulting from lower thickness of web. When exposed to fire, moment and shear capacity of Beams 2, 4 and 5 starts to degrade after 9, 7 and 6 min of fire exposure time as shown in Fig. 11. Although, all beams experience strength and stiffness degradation due to temperature rise, the rate of degradation is slightly higher in Beams 4 and 5 due to faster rise in temperature in web as shown in Fig. 10.



(a) Moment capacity

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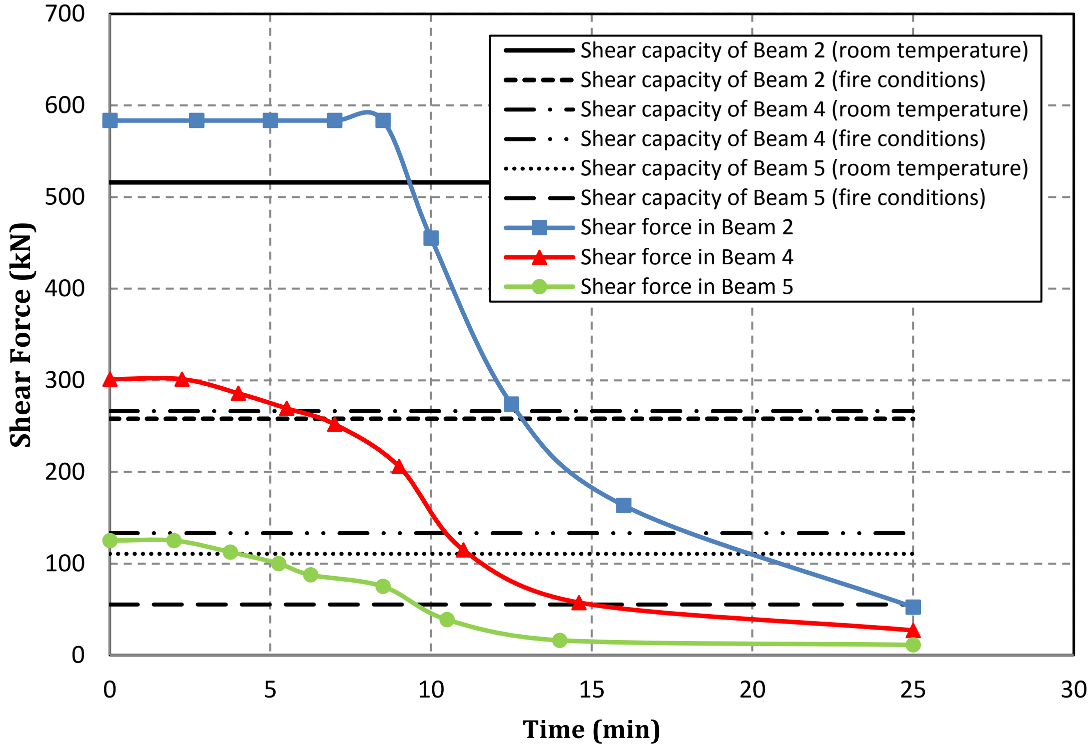

(b) Shear capacity

Fig. 11. Degradation of bending and shear capacity with fire exposure time in beams with varying slenderness ratio

Figure 12 compares predicted mid-span deflection in Beams 2, 4 and 5. In general, mid-span deflections are small in the initial stage of fire exposure and then increases gradually with fire exposure time. The deflections increase at a rapid pace towards final stage of exposure due to very high temperature in steel, and this lead to failure of beams. As expected Beams 4 and 5, with higher web slenderness, undergo larger initial deflections as compared to that of “Beam 2”.

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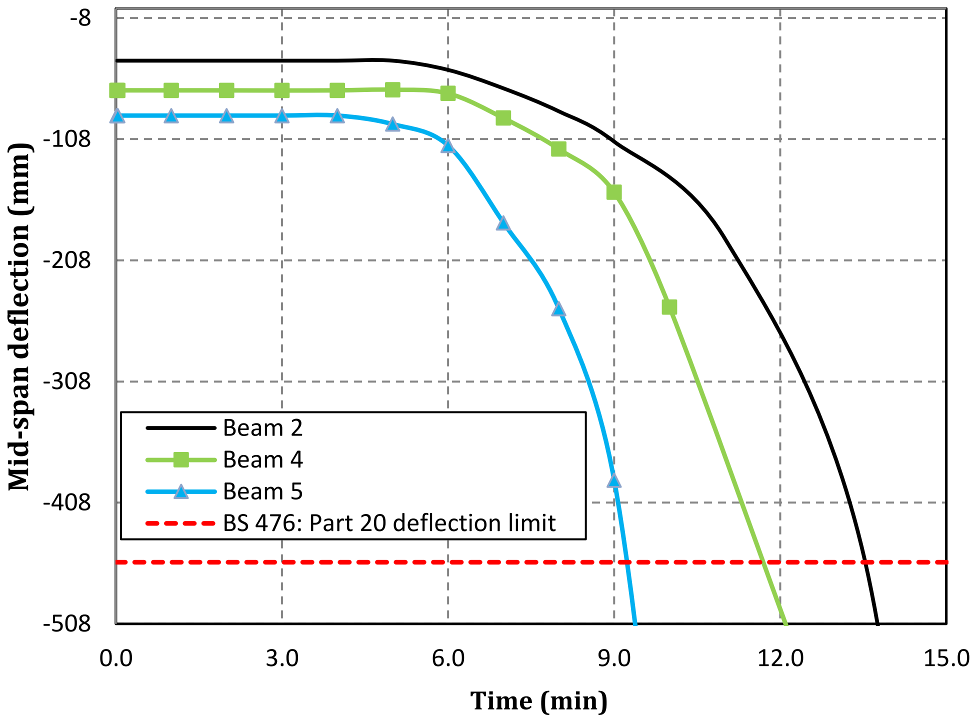

Fig. 12. Comparison of mid-span deflections in Beams 2, 4 and 5 with different web slendernesses

Beams 4 and 5 experience failure through flexural limit state at 12.5 and 11.5 min, as compared to 14 min in Beam 2. Further, these beams (4 and 5) fail in shear at 7 and 11 min. The mid-span deflection in "Beam 4" when the shear capacity exceeds at 11 min is 408 mm, while corresponding mid-span deflection in "Beam 5" at 7 min (at failure) is 177 mm. This indicates that beams 4 and 5 fail at lower mid-span deflection and at earlier times as compared to that of "Beam 2". Table 3 summarizes failure modes in these three beams analyzed with different web slenderness. These results clearly illustrate that web slenderness influences failure mode in fire exposed steel beams and can lead to shear failure.

Table 3 Failure in beams with different web slenderness

Beam			Failure time (min)	Failure mode

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	Web slenderness	Flange slenderness	Shear	Flexure	Deflection	
Beam 2	57.82	6.28	13	14	13.8	Shear
Beam 4	75.10	6.28	11	12.5	11.7	Shear
Beam 5	100.13	6.28	7	11.5	9.3	Shear

6.3 Effect of fire insulation

The above results clearly illustrate that under fire exposure, shear failure can occur in beams prior to attaining flexural or deflection limit state under certain loading configuration and high web slenderness. However, if the beams are insulated, the time to failure can be reduced significantly. In order to study the effect of fire insulation two beams, "Beam 6" and "Beam 7" protected with 19.05 mm and 25.4 mm thick vermiculite/gypsum (VG) insulation, were analyzed by subjecting them to combined fire and structural loading, and failure time is evaluated. These beams have the same geometry, material properties as well as loading configuration of "Beam 2". The thermal conductivity and specific heat of fire insulation is 0.0815 W/m.˚C and 1047 J/kg.K, respectively. Figure 13 shows a discretized view of "Beam 6" with fire insulation.

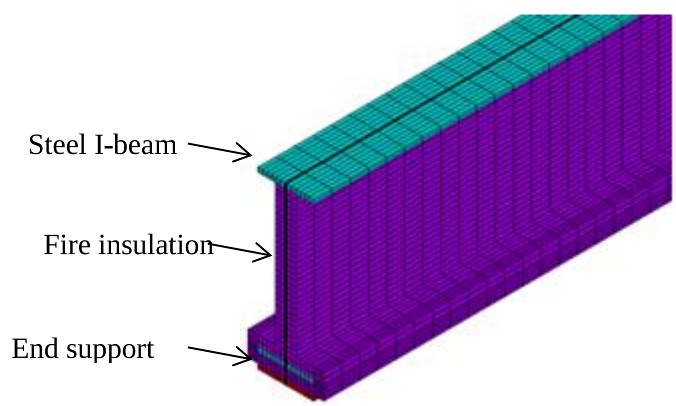

Fig. 13. Detailed view of fire insulated steel "Beam 6"

In general, the presence of fire insulation delays temperature rise in steel beams which in turn delays strength and stiffness degradation in steel. As can be seen in Fig. 14, temperature rise in Beams 6 and 7 are much slower than of that observed in “Beam 2” throughout fire exposure time. Further, Beams 6 and 7 experience similar rise in web temperature during first 5 minutes into fire. However, after 5 minutes, web temperature in “Beam 6” increases at a faster pace than that of “Beam 7” and this is mainly due to the thinner fire protection applied on “Beam 6”.

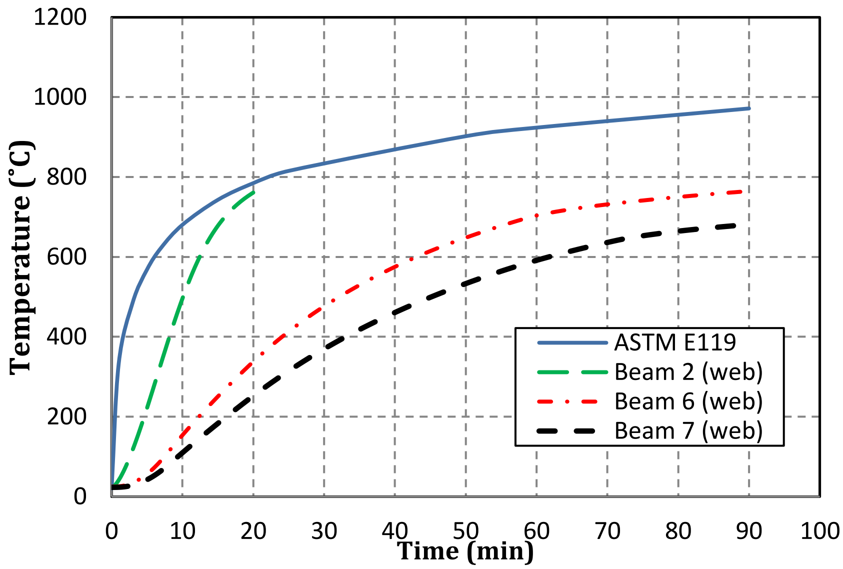

Fig. 14. Predicted temperature propagation of Beams 2, 6 and 7

The lower temperature in insulated Beams 6 and 7 leads to slower degradation in moment and shear capacity as compared to that in “Beam 2” which is uninsulated (see Fig. 15). Degradation of moment and shear capacity starts at 26 and 33 min for Beams 6 and 7, respectively; a significant increase than that in “Beam 2” where degradation starts at 9 min. This leads to enhanced failure time in Beams 6 and 7.

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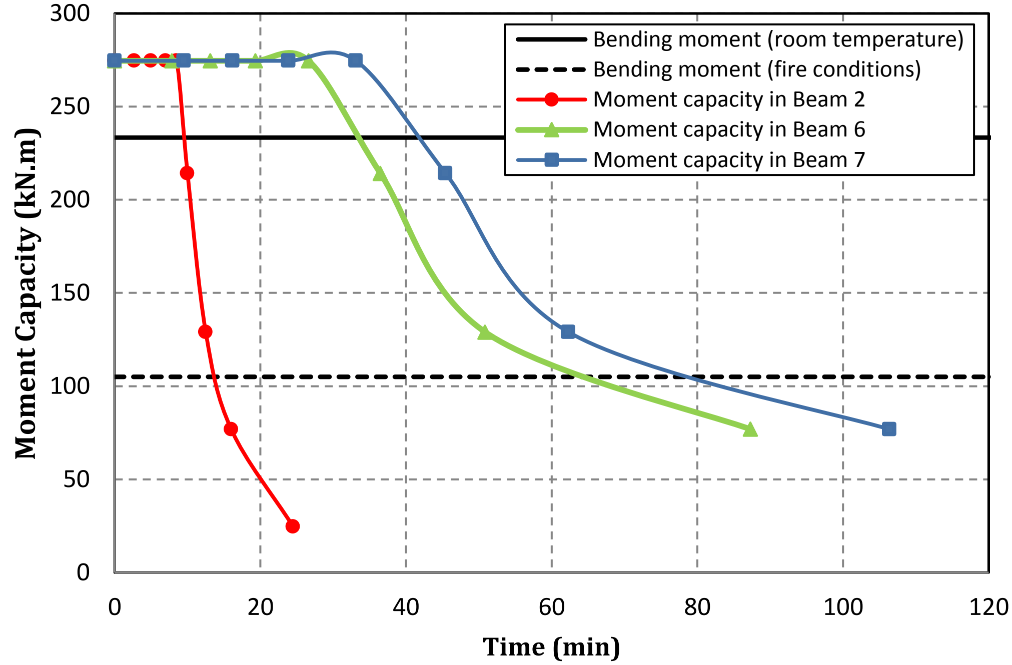
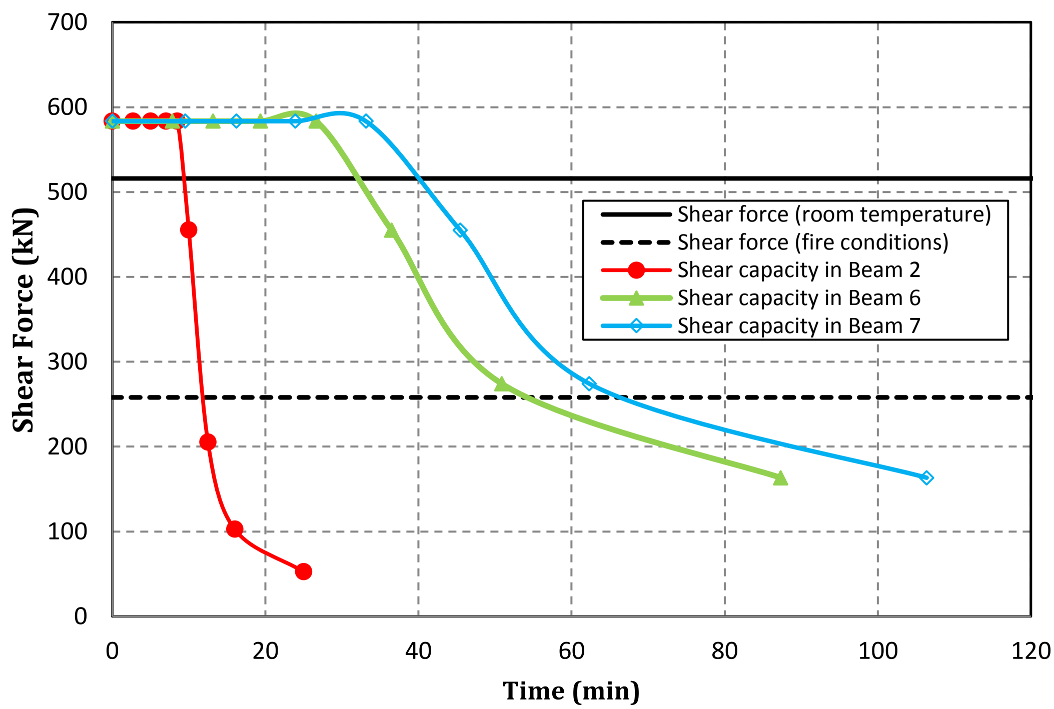


(a) Moment capacity



(b) Shear capacity

Fig. 15. Degradation of flexural and shear capacities in Beams 2, 6 and 7

Figure 16 shows a comparison of mid-span deflection in Beams 2, 6 and 7. The presence of fire insulation significantly enhanced structural response of insulated beams as can be seen through lower deflection throughout fire exposure duration. The insulated beams experienced significantly lower deflection at failure as compared to that of un-insulated "Beam 2". In general, mid-span deflection of Beams 6 and 7 increased gradually with fire exposure time and there is no runaway failure in these beams, till 60 and 70 minutes, respectively.

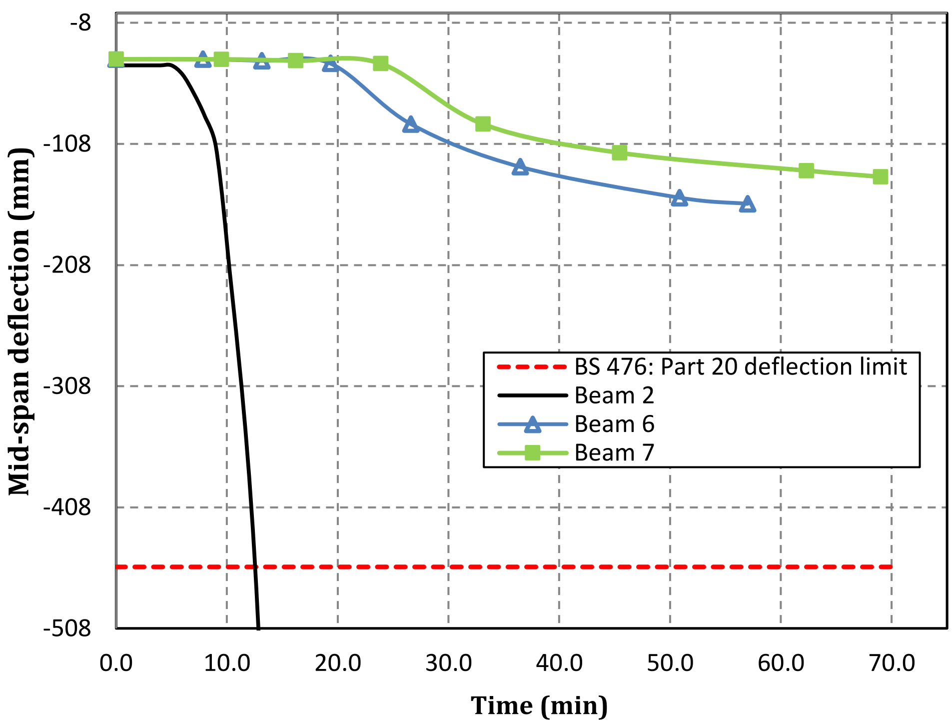


Fig. 16. Comparison of mid-span deflection in Beams 2, 6 and 7

Failure in Beams 2, 6 and 7 occurred at 14.5, 65 and 78 min under flexural limit state, respectively. On the other hand, failure under shear limit state occurred at 13, 55 and 67 min for These beams. It can be seen that the mode of failure through shear limit state did not change when

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Beams 6 and 7 were provided with fire insulation, however the time to failure substantially increased due to slow down in temperature rise in steel beams. Further, both Beams 6 and 7 achieved 1-hour fire rating, as per prescriptive criterion under flexural limit state. However, "Beam 6" does not yield 1-hour fire rating under shear limit state. Therefore, shear failure can significantly lower failure times which in turn may lead to unconservative fire resistance under certain scenarios. Table 4 shows failure times in Beams 2, 6 and 7.

Table 4 Failure time in Beams 2, 6 and 7 under different limit states

Beam	Insulation (mm)	Failure time (min)			Failure mode
		Shear	Flexure	Deflection	
Beam 2	None	**13**	14	13.8	Shear
Beam 6	19.05	**55**	65	-	Shear
Beam 7	25.4	**67**	78	-	Shear

7.0 CONCLUSIONS

Based on the results of the analysis presented herein, the following conclusions can be drawn:

1. Effect of shear force can dominate fire response of steel beams subjected to high concentrated loads close to supports. In such scenarios, failure of a fire exposed beam can occur under shear limit state rather than flexural limit state.

2. The proposed finite element model is capable of predicting the fire response of steel beams where shear effects dominate the behavior of steel beams.

3. Higher slenderness of webs can lead to rapid degradation of shear capacity, at a higher pace than that of moment capacity, in fire exposed steel beams.

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4. Use of fire insulation can significantly enhance fire performance of steel beams; however, high shear loading, combined with lower slenderness in webs, can significantly lower fire resistance which in turn can lead to unconservative fire resistance under certain scenarios

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