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Performance of solid steel beam under fire for different beam slenderness

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Abstract

The present work is intended to study the behaviour of solid steel beam (SSB) under the ISO834 fire curve for different beam slenderness when it is subjected to three-sided exposure and four-sided exposure condition. The properly validated finite element based thermo-mechanical analysis is carried out to predict the performance of SSB under elevated temperature. The present study takes into account the transient temperature effect and the geometrical and material non-linearity. The section selected for this study is a universal beam section UB356×127×39. The considered beam slenderness (span to depth ratio) for this study is varied between 15 to 35, as these slenderness are generally preferred in practice. The eccentric hinge-hinge boundary conditions at the bottom flange are applied to the beam and beam is assumed to be laterally supported at top flange all along its length, and the bottom flange is not restrained laterally along its length. The various parameters considered for the present study include: beam slenderness, load ratios, and exposure condition of the beam under uniformly distributed loading. The performance of SSB under fire is compared using mid-span deflection, lateral displacement, limiting deflection, limiting temperature, and fire resistance time of the SSBs. This study depicts that there is a significant effect of beam slenderness on the behavioural aspect of SSB under elevated temperature.

Keywords: Beam slenderness, ISO834 fire curve, limiting temperature, fire resistance time, hinge-hinge.

1. Introduction

In recent years, with growing demands for the shortening in the construction time and the efficient use of available space; the need to adopting steel material is becoming increasingly significant. Therefore, steel structures are widely used in construction due to the advantages of its high strength, ductility, and fast fabrication and erection. However, without fire protection steel structures may suffer from serious damage or collapse in a catastrophic fire condition.This is because the mechanical properties of carbon steel deteriorate at elevated temperatures and the yield strength of conventional steel at 600 ^{0}C is less than one-third of the specified yield strength at room temperature [1]. Under such fire conditions, the load-bearing capacity of beam drops, leading to certain deformation and fails.The time to reach this failure is referred to as fire resistance time [2]. The various studies had been performed on the behaviour of steel beams in fire by conducting experimental and numerical investigations with different spans and the support conditions to determine the survival time [3]. The bucking issues related to steel beams under fire adds complexity in determining the survival time of member. The fundamental structural behaviour of steel beam under thermal effect was explained and reported in [4]. There have been some recent efforts to study numerically the effect of axial restraint on fire response of steel beam and concluded that restraint effect and catenary action has significant improvement on resistance time [5-6]. By using the fire coatings, the resistance time of steel beams under the standard fire was investigated through fully coupled thermo-mechanical numerical analyses up to the occurrence of the run-away deflection [7].The temperature gradients within a steel beam may have a detrimental effect on the lateral-torsionalbuckling capacity of the beams in a fire [8].Many studies are done in the past about the behaviour of steel beams under fire exposure conditions. All the recent studies are done by considering the different parameters like support conditions, load ratios and fire-resistant coatings on steel members. But a very less research work is available on the bare steel beam by considering the effect of beam slenderness under fire [9-12].

In the present work, a parametric study is done, on unprotected steel beam exposed to three-sided and four-sided exposure fire conditions under standard time-temperature fire curve. A series of numerical thermo-mechanical analyses are carried out on UB356×127×39 beam section with beam slenderness ratio (L/D) ranging from 15 to 35 and having eccentric hinge – hinge boundary conditions applied at the bottom flange of the cross-section.

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Table-1. Considered parameters for SSB under different fire exposure conditions

L/D	Beam length (mm)	Load Ratio (LR)	Exposure conditions
15	5301	0.5, 0.7	3-sided and 4-sided
20	7068	0.5, 0.7	
25	8835	0.5, 0.7	
30	10602	0.5, 0.7	
35	12369	0.5, 0.7	

The beam is assumed to be laterally restrained along the member length. The various parameters considered for the present study include: different beam slenderness, different load ratios as 0.5 and 0.7 [6], and exposure conditions as shown in Table 1. The beam is assumed to be loaded under uniformly distributed load at ambient temperature and also during fire conditions. In all twenty numbers of FE, simulations have been performed to understand the behaviour of SSB accounting the effect of beam slenderness. A finite element tool is adopted, in which various factors affecting the behaviour in a fire can be included. Among these, the various influencing factors such as non-linear material behaviour, geometric non-linearity, non-uniform temperature distributions, and thermal strains are considered in all these nonlinear finite element analyses.

2. Validation of thermo-mechanical modelling

The numerical simulation used for carrying out the present study is first validated by comparing the results obtained from presently developed finite element simulation with available experimental work done by Rubert and Schaumann [13], and also withnumerical simulation conducted by Iu and Chan [14]. In [13], thetest wasperformed to investigate the behaviour of a steel beam for simple bending problem by the applied point load.A 1.14 m long simply supported beam behaviour under various load ratios was investigated and further its numerical simulation is done in[14]. TheIPE 80 section was used for beam and it was subjected to a concentrated load at the mid-span and heated uniformly along the entire length.The thermo-mechanical model developed for the present study isvalidated by comparing the experimental results mentioned in [13], and also with simulationresultsmentioned in [14] forthe beam with aloadratioof 0.2 and represented in Fig. 1.

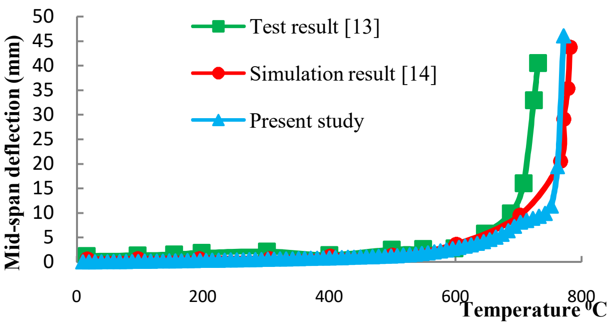

Fig. 1. Comparison of results - mid-span vertical deflection verse temperature

The overall prediction of the temperature–deflection curve from the fully coupled thermo-mechanical analysis correlates well with both [13 and14] results. The deflection of the test specimen increases abruptly when the temperature of the web reaches about 700 ^{0}C. The temperature of run-away deflection predicted by this study is almost identical to that observed in both test and simulation outcomes.

3. Finite element model

ANSYS [15] is used for analysing the non-linear behaviour of various steel beams at elevated temperatures and having parametric variations reported in Table; with the input of material properties and stress-strain relationships at high temperaturesas mentioned in EC3[16].

3.1 Basic elements

The following elements fromthe ANSYS library are adopted for both thermal and structural model. The parametric study is conducted for exploring the performance of steel beams for various beam slenderness at elevated temperature.

3.2 Thermal element

SHELL131 is a 3-D layered shell element having in-plane and through-thickness thermal conduction capability. The element has four nodes with up to 32 temperature degrees of freedom at each node as shown in Fig. 2. This shell element is capable of conducting 3D steady-state or transient thermal analysis. SHELL131 generates temperatures that can be passed to structural shell elements to model thermal bending

3.3 Thermal surface element

SURF152 element (refer Fig. 3)can be used for various load and surface effect applications. It may be overlaid onto an area face of any 3-D thermal element. The element is applicable to 3-D thermal analyses. Various loads and surface effects may exist simultaneously. The element is defined by four to ten nodes and the material properties. An extra node (away from the base element) may be used for convection or radiation effects. Two extra nodes (away from the base element) may be used to more accurately capture convection effects.

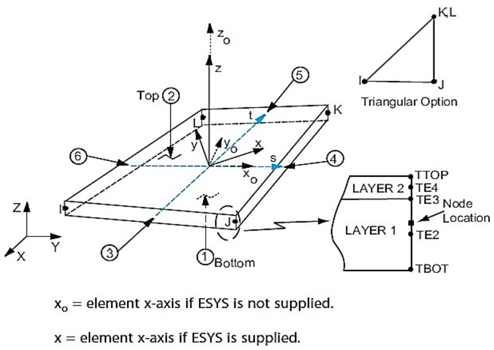

Fig. 2. SHELL131 3-D layered shell element- ANSYS [15]

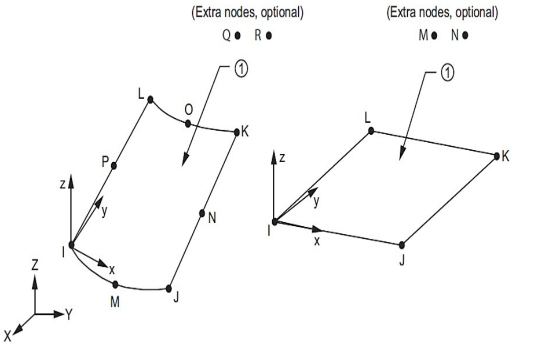

Fig. 3. SURF152 3D geometry- ANSYS [15]

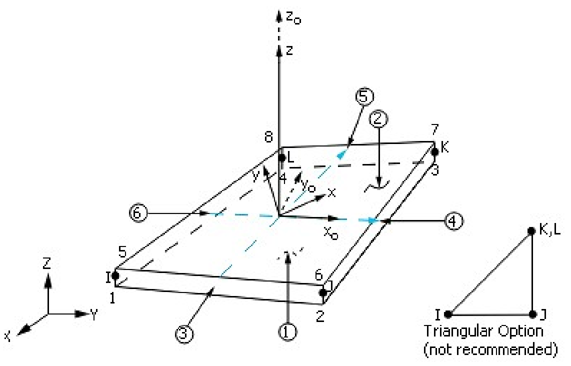

Fig. 4. SHELL181 3-D layered shell element- ANSYS [15]

3.4 *Structural element*

SHELL181 element is suitable for analysing thin to moderately-thick shell structures. It is a four-node element with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z-axes as shown in Fig. 4. SHELL181 element is well suited for linear, large rotation, and/or large strain nonlinear applications. Change in shell thickness is accounted for in nonlinear analyses. In the element domain, both full and reduced integration schemes are supported. The geometry, node locations, and the element coordinate system for this elementare shown in Fig. 4. The element is defined by shell section information and by four nodes (I, J, K, and L).

4. Thermo-mechanical simulation

A systematic parametric thermo-mechanical analysis is conducted by following the procedures presented below. The first step of the analysis is to define the standard fire curve. The standard ISO834 [17] time-temperature curve is used in this study. The second step is to determine the heat transfer within the steel and at the fire exposed surface area depending on the exposure conditions of the steel section. The last step is to relate the increasing temperature with time to the structural responses of steel beams. Afully coupled thermo-mechanical analysis is then performed.

4.1 *Standard time-temperature fire curve*

The standard time-temperature curve used in fire resistance test is called standard fire. The most widely used test specifications are ISO834 [17] and ASTM E119 [18]. A real fire curve is characterized by three phases: a pre-flashover, a fully developed phase and decay phase. Most of the structures are failed in fully developed phase and it is taken into account in the present study. The fireloadinthisstudyis assumed tofollowthestandard time-temperature curve as mentioned in ISO834 [17]; sinceitisthe representative fire modelusedin design practice. The furnace time-temperature relationship of ISO834can be calculated using the following (Eq. 1), where T_g is the gas temperature in ^{0}C and t is time in minutes.

$$T_g = 20 + 345\ log_{10}(8t+1) \quad (1)$$

4.2 *Heat transfer model*

The temperature distribution within the steel beam section has a significant effect on the section factor of a steel beam at elevated temperatures. Traditionally, the section factor, whichisdefinedasthelengthoftheheated perimeter dividedbythesectional area, hasbeenused as an influencingfactoronthetemperaturedistribution within the beam section.The transient thermal analysis isrequiredtodetermine the temperature distribution within the steel and at the fire-exposed surface area. The temperature distribution in steel depends upon the thermal properties, such as; thermal conductivity and specific heat; and thermal load. In thermal simulations, a temperature-dependent property ofthermal conductivity (*kin* W/mK) is specified using (Eq. 1 and Eq. 2),andspecific heat (c_p in J/kgK) are specified using (Eq. 4 - Eq. 7), as per EC3 [16].The density of steel is 7850 kg/m^3, which is assumed to be independent on temperature. The Stefan–Boltzmann radiation constant is σ =5.67×10^{-8} W/ (m^{2}K^4). The thermal load accounts the radiation with the emissivity value ε_r= 0.75 at steel surface, and convective heat transfer coefficient h_c = 4W/m^{2}K; and 25W/m^{2}K for room temperature and fire temperature, respectively [16]. Then the time-temperature dependant standard ISO834 curve as per (Eq. 1)is applied as source fireto carry out the thermal analysis by considering the effect of thermal radiation and thermal convection.

$$k = 54 - 0.0333T \quad 20\,^0C \le T \le 800\,^0C \quad (2)$$

$$k = 27.3 \quad 800\,^0C \le T \le 1200\,^0C \quad (3)$$

$$c_p = 425 + 0.773T - 1.69\times10^{-3}T^2 + 2.22\times10^{-6}\,T^3 \quad (4)$$
$$20\,^0C \le T < 600\,^0C$$

$$c_p = 666 + 13002\,/\,(738 - T) \quad (5)$$
$$600\,^0C \le T < 735^0C$$

$$c_p = 545 + 17820\,/\,(T - 731) \quad (6)$$
$$735\,^0C \le T < 900\,^0C$$

$$c_p = 650 \quad 900\,^0C \le T \le 1200^0C \quad (7)$$

4.3 Structural model

The UB356×127×39 steel section is chosen for parametric study (depth of the section =353.4 mm, width of the flange =126 mm, web thickness = 6.6 mm and flange thickness = 10.7 mm). The yield strength (σ_y) and the modulus of elasticity (E) of the steel beam at ambient temperature are 355 MPa [19] and 2.05×10^5 MPa, respectively.The considered degradation in yield strength and modulus of elasticity of steel with risingtemperature is as per EC3 [16] and represented in Fig. 5(a). The coefficient of thermal expansion for steel $\alpha=14\times10^{-6}$ / ^{0}C as reported in EC3 [16] is used in the present study. Stress-strain relationships at elevated temperatures can be obtained directly from steady-state tests at certain elevated temperatures or they can be derived from the results of transient tests. Transient state temperaturedependent stress-strain relations under elevated temperature for steel as reported in EC3 [16] are used and shown in Fig. 5(b).

4.4 Procedure for thermo-mechanical analysis

The discretization of the solid steel beam (SSB) with eccentric boundary conditions with applied uniformly distributed load and lateral restraint over the entire length of the beam is shown in Fig. 6. The beam is loaded withuniformly distributed load required to achieve the LR at its ambient temperature.The FE analysis is carried out to obtain the structural response under ambient temperature 20 ^{0}C by applying static uniformly distributed load on the top flange of the SSB. Thethermal load was applied to the fire exposed

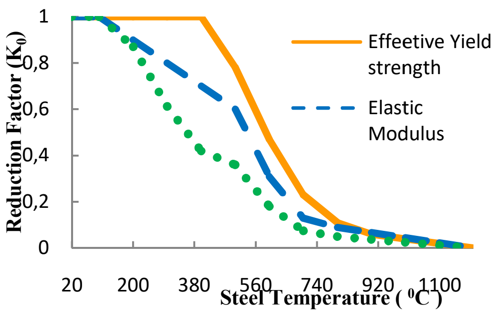

Fig. 5(a). Reduction factors for E and $\sigma_y$at high temperatures

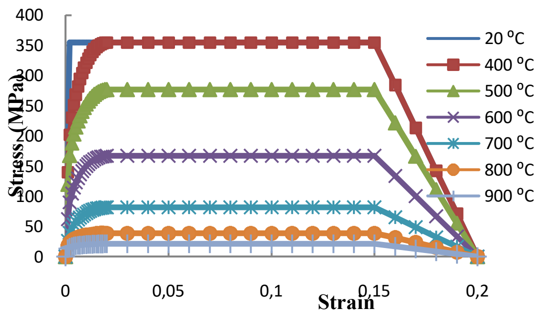

Fig. 5 (b). Stress-strain relationship of carbon steel at high temperatures

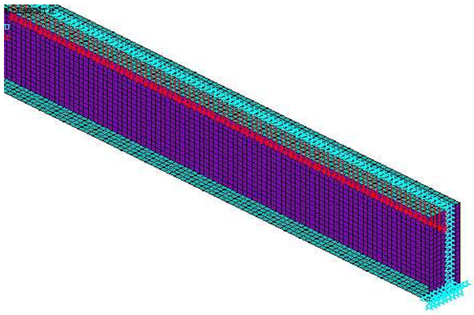

Fig. 6. Discretization of solid steel beam with boundary conditions

surfaces. The steel temperature at every node location is obtained for every time step from the thermal analysis. Then these temperatures were applied to corresponding nodes of structural shell elements on meshed beam. Finally, the nonlinear (material nonlinearity and geometry nonlinearity) analysis is carried out to obtain the total structural response under elevated temperature.The nonlinear convergence study is required to overcome the convergence criteria during analysis time. It was found that shell element with the mesh of size 20 mm gives good convergence result and less computational time. Newton- Raphson method is adopted for nonlinear analysis.

5. Numerical analysis of SSB at elevated temperatures

The unprotected steel beam is subjected to material degradation characteristics under elevated temperaturewhich often suffer large deformation and undergoes complicated behaviour during the realistic fire. Finite element (FE) simulations can be used efficiently to examine the behaviour of SSB for various beam slenderness under fire. The FE model is developed to investigate the influence of significant parameters on theresponse of unprotected laterally restrained SSB with eccentric hinge-hinge boundary conditions under standard fire (ISO834). The factors considered in this study are: the load ratio(LR) as 0.5 and 0.7, beam slenderness ratio(L/D) ranging from 15 to 35, and fire scenario (three-sided and four-sided exposure) by considering material nonlinearity at higher temperatures as mentioned in section 4. The present numerical study considers three-sided exposure condition that means the surfaces of the weband flanges except for the top of the upper flange and supports areexposedto fire, four-sided exposure condition that meansall the surfaces of the web and flanges are exposed to fire. In structural analysis, the load ratio is defined as the ratio of the maximum bending moment at ambient temperatures to the plastic moment capacity of the beam at ambient temperature. The temperature distribution in steel beam with beam slenderness L/D = 20 under three-sided exposure, and four-sided exposure conditions for 20 minutes fire duration is as shown in Fig. 7(a), and Fig. 7(b); respectively. It can be observed from these figures that a similar temperature is attained in the webfor both the considered exposure conditions and also for the bottom flange for both the considered exposure conditions. The temperature attained intop flange is higher for four-sided exposure condition than that for three-sided exposure condition.

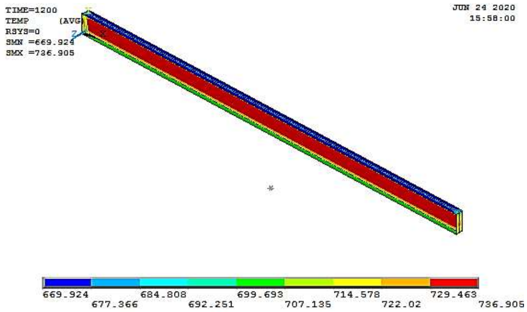

Fig. 7 (a). Temperature distribution in steel beam for three-sided exposure

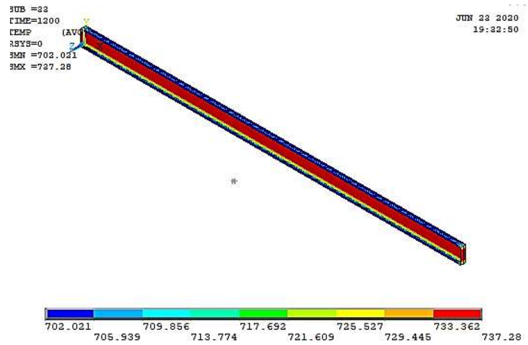

Fig. 7 (b). Temperature distribution in steel beam for four-sided exposure

6. The response of SSB under three-sided and four-sided fire scenario

A numerical study is performed to determine thebehaviour of SSB at elevated temperature for ISO834 curve under three-sided, and also under four-sided exposure for eccentric hinge-hinge boundary conditions applied at the bottom flange. The response of CSB can be found out by mid-span deflection, lateral displacement and limiting deflection as failure criteria concerning to fire resistance time.

6.1 Deflection of SSB for three-sided and four-sided exposure under fire

Heating induces the thermal expansion in the un-restrained structural steel elements. Provision of boundary conditions develops the restraining actions in the beam and results in the development of mechanical strain if the member is subjected to heating. In the present study, the analysis is performed by considering the axial restraint by simulating eccentric hinge-hinge boundary conditions at the bottom flange of the section. The developed mechanical strains in the beam under fire can be divided into two types namely: primary mechanical strains produced by mechanical loading, and secondary mechanical strains induced due to the axial restraint condition under thermal expansion; and also due to the development of moment because of eccentric boundary conditions. The complexity in understanding the behaviour of SSB under fire is increased due to the fact that the steel material loses its strength at a higher temperature, and also due to the beam-column response developed on account of the presence of eccentric boundary conditions. The behavioural aspect in terms of mid-span deflections of SSB under fire considering the effect of beam slenderness is shown in Fig .8(a) and 8(b); for LR 0.5 and 0.7 under three-sided exposure; respectively. The behavioural aspect in terms of mid-span deflections of SSB under fire considering the effect of beam slenderness is shown in Fig .9(a) and 9(b); for LR 0.5 and 0.7 under four-sided exposure; respectively.

Initially up to four minutes, for all considered beams having different slenderness, the response of SSB isrepresenting the upward mid-span deflectiondeveloped on account of increase in temperature of the beam and the eccentric boundary conditions. After four minutes, theenhanced

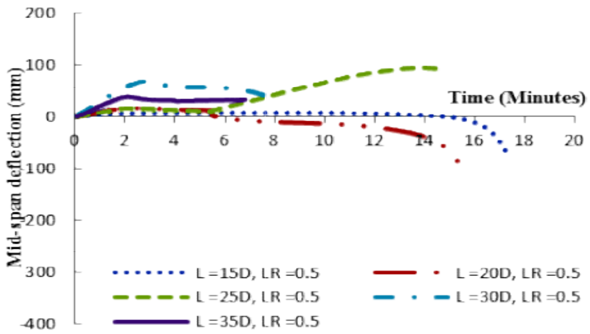

Fig. 8 (a) Behavioural aspect mid-span deflection for three-sided exposure of SSB when LR =0.5.

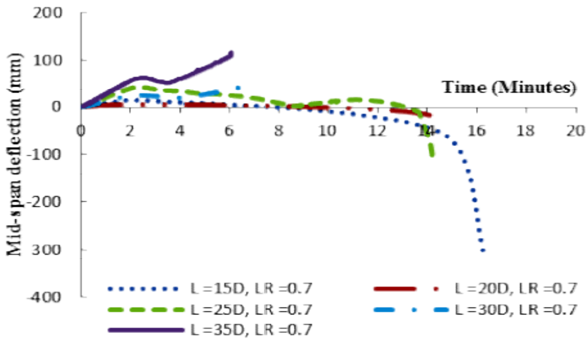

Fig. 8 (b) Behavioural aspect on mid-span deflection for three-sided exposure of SSB when LR =0.7.

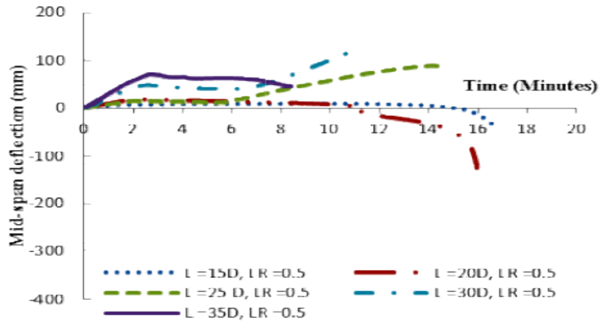

Fig. 9 (a) Behavioural aspect on mid-span deflection for four-sided exposure of SSB when LR =0.5.

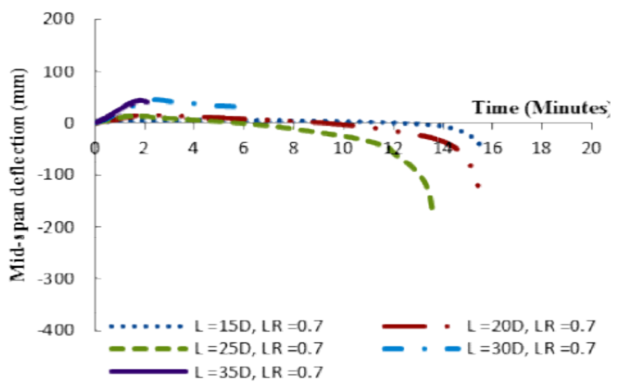

Fig. 9 (b) Behavioural aspect on mid-span deflection for four-sided exposure of SSB when LR =0.7

mechanical strainsand their distribution results in downward deflection of beams for beam slenderness equal to 15, 20 and 25. The beams with higher L/D ratio that is 30 and 35, are failed earlier and having lesser resistance time. This shows that the beams having higher slenderness are prone to fail early within four to six minutes. The beams with lower slenderness are having higher resistance time.

The bottom flange is not laterally restrained and imposed eccentric boundary condition of SSB resulted into lateral displacements of the bottom flange and web of SSB due to restrained thermal expansion at beam ends. This tendency of lateral displacement is enhanced in the long span beams under fire. The behavioural aspect of SSB with lateral displacement is shown in Fig. 10(a) and 10(b), for LR 0.5 and 0.7 under three-sided exposure; respectively. By comparing these figures, it is observed that the time versus lateral displacement plot have three distinct regions, namely: initial portion without lateral displacement, non-linear portion, and portion showing run away lateral displacements that means displacements are increasing without any appreciable change in time. The presence or absence of these three distinct categories of load and lateral displacement also depends on the beam slenderness and LR. For example, from figure 10 (a), beam with L/D ratio equal to 15 and 20, shows nolateral displacements for most of the portion before the occurrence of failure and their resistance time is high. The beam with L/D ratio that is equal to 25, all three aforementioned branches of load versus time are visible. The beams with an L/D ratio that is equal to 30 and 35, the runaway lateral displacement branch is not observed. From fig. 10(b) when LR is 0.7, allthree aforementioned branches of load versus time are present. The nonlinear part and runaway displacement branch are initiated at an earlier time for more slender beams. The behavioural aspect of SSB with lateral displacement is shown in Fig. 11(a) and 11(b), for LR 0.5 and 0.7 under four-sided exposure; respectively. The all three aforementioned branches of load versus time are present in Fig. 11(a) for LR equal to 0.5. Fig. 11(b) shows that the runaway displacement branch is initiated after the completion of no displacement branch having a very negligible part of nonlinear lateral displacement behaviour inbetween. From the present study, it is observed that it is better to keep the beam slenderness in the range of 15 to 25 and also to maintain LR below 0.5 to avoid the buckling of lower flange under fire for eccentric boundary conditions.Moreover, these observations are based on a three-sided heating scenario, which will occur if the reinforced concrete slab is available at the top flange of SSB.

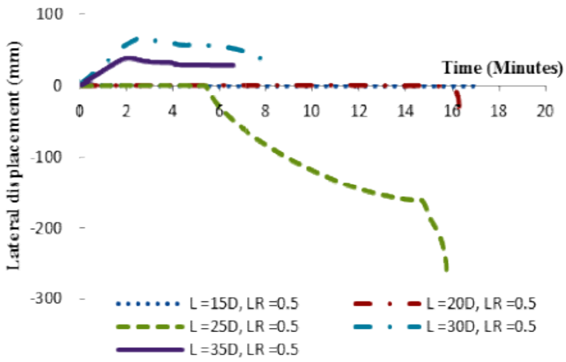

Fig. 10 (a) Behavioural aspect on lateral displacement for three-sided exposure of SSB when LR =0.5.

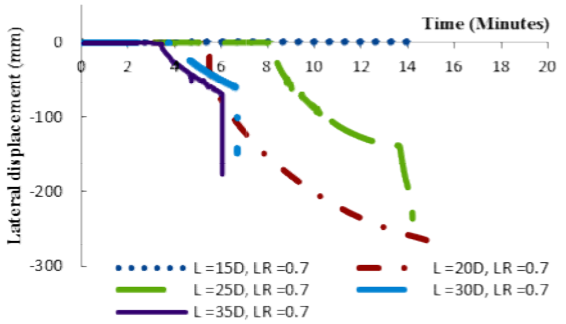

Fig. 10 (b) Behavioural aspect on lateral displacement for three-sided exposure of SSB when LR =0.7.

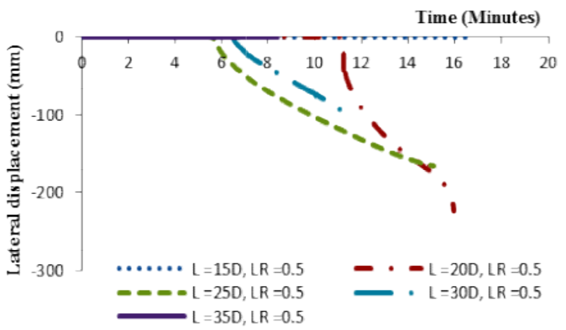

Fig. 11(a) Behavioural aspect on lateral displacement for four-sided exposure of SSB when LR =0.5.

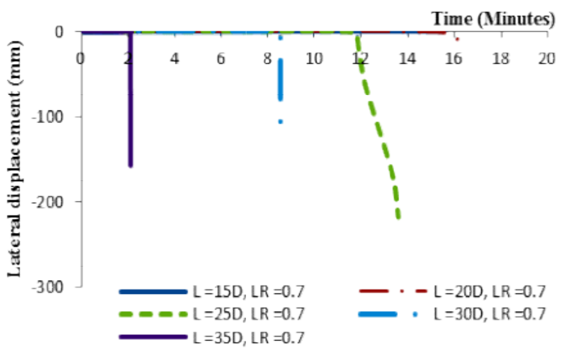

Fig. 11(b) Behavioural aspect on lateral displacement for four-sided exposure of SSB when LR =0.7.

Table-3. Limiting temperature of SSB for bottom flange under three-sided and four-sided fire exposure

L/D	LR	3 sided exposure ^{0}C	4 sided exposure ^{0}C
15	0.5	664	650
	0.7	640	623
20	0.5	630	638
	0.7	631	603
25	0.5	610	605
	0.7	595	582
30	0.5	360	507
	0.7	315	280
35	0.5	318	411
	0.7	300	100

7. Discussion on results of SSB under fire exposure conditions

In this study, the response of SSB has been studied numerically considering various factors: beam slenderness, LR's, and exposure condition having eccentric hinge-hinge boundary conditions under thermal effect. As per BS5950 [20], the commonly specified failure criteria is a limiting deflection of L/20 of the span (L). Due to nonlinearity and material degradation properties, the strength of any member loses its load-carrying capacity. In the present study, the numerical models of SSBs are failed before attaining this specified limiting deflection values and thus does not govern the failure of SSBs. The limiting deflection values based on L/20 criteria and corresponding mid-span in-plane deflections of SSBs at failure stage obtained from numerical analysis are shown in Table 2 for SSBs for all considered beam slenderness, load ratios, and fire exposure conditions. The positive values of deflection inTable 2 indicate the upward deflection of the SSBsunder fire.The temperature at which the member loses its load- carrying capacity is called as limiting temperatureaccording to AS 4100 [21]. Due to the presence of eccentric boundary conditions, the lower flange of the slender beam is experiencing large lateral displacements before failure andhence the temperature attained in the bottom flange isconsidered as limiting temperature.The limiting temperature is shown in Table-3for considered beam slenderness,loadratios under three-sided and four sided fire exposure conditions. The effect of load ratio has negligible influence on limiting temperature for beams having slenderness 15 to 25. For slender beams (having L/D =30 or 35) considerable variation in limiting temperature under three-sided and four-sided exposure conditions is observed. Thus, it can be observed that the difference in limiting temperature of SSB increases with an increase in beam slenderness. A large difference in limitingtemperature is observed for two extreme casesof considered beam slenderness i.e. 15 and 35.

Table-4. Fire resistance time of SSB under three-sided and four-sided fire exposure

L/D	Load Ratio (LR)	Fire resistance time (Minutes)	
		3-sided	4-sided
15	0.5	17.25	16.73
	0.7	16.29	15.4
20	0.5	15.43	15.9
	0.7	15.57	14.35
25	0.5	14.71	14.72
	0.7	14.20	13.59
30	0.5	7.82	11.08
	0.7	6.59	5.85
35	0.5	6.68	8.21
	0.7	6.01	2.12

Thefire resistance time of SSBfor all considered beamslenderness, load ratios under three-sided and four-sided fire exposure conditionsare shown in Table-4.The resistance time of SSB depends on beam slenderness, LR, and exposure conditions. Moreover, the resistance time for four-sided exposure condition is less than that for three-sided exposure condition.The effect of load ratio onresistance time of SSBs is not appreciable for beams slenderness ranging from 15 to 25. The load ratio is significantly affecting the resistance time of SSBs having slenderness equal to 30 and 35 for four-sided exposure condition.

8. Conclusions

In present work, a numerical study is performed to determine the behaviour of SSB at elevated temperaturedue to the ISO834 curve. A series of thermo-mechanicalnumerical analysis is performed for SSB UB356×127×39 beam section and having eccentric hinge-hinge boundary conditions applied at the bottom flange. The various parameters considered for the present study includes: beam slenderness ratio (L/D) ranging from 15 to 35, different load ratios as 0.5 and 0.7, and different exposure conditions that is three-sided and four-sided exposure under uniformly distributed loading condition. The finite element model is first developed and validated with both experimental and simulation resultsmentioned in [13-14]. Overall, the results are agreed well and hence further numerical models are developed for carrying out the parametric study. The response of SSB is determined by comparing mid-span deflections, andlateral displacements. The significant conclusions drawn from present study are:

- The longer span beams having L/D ratio equal to 30, and 35 are sensitive to lateral displacements of bottom flange and web; under three-sided and four-sided heating. This is occurring due to buckling of lower flange, which in turn is taking place due to the presence of eccentrichinge-hinge boundary conditions. The beams with higher L/D ratio that is 30, and 35; are failed earlier and having lesser resistance time. The beams with lower slenderness is having higher resistance time.

- The effect of load ratio onresistance time of SSBs is not appreciable for beams slenderness ranging from 15 to 25. The load ratio is significantly affecting the resistance time of SSBs having slenderness equal to 30 and 35 for four-sided exposure condition.

- The difference in limiting temperature of SSB increases with an increase in beam slenderness. A large difference in limiting temperature is observed for two extreme cases of considered beam slenderness i.e. 15 and 35.

Disclosures

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