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Response of Fire Exposed Composite Girders under Dominant Flexural and Shear Loading

Naser M.Z.^{1,*} Kodur V.K.R.

1.0 ABSTRACT

This paper presents results from numerical studies on the response of fire exposed composite girders subjected to dominant flexural and shear loading. A finite element based numerical model was developed to trace the thermal and structural response of composite girders subjected to simultaneous structural loading and fire exposure. This model accounts for various critical parameters including material and geometrical nonlinearities, property degradation at elevated temperatures, shear effects, composite interaction between concrete slab and steel girder, as well as temperature-induced local buckling. To generate test data for validation of the model, three composite girders, each comprising of hot-rolled (standard) steel girder underneath a concrete slab, were tested under simultaneous fire and gravity loading. The validated model was then applied to investigate the effect of initial geometric imperfections, load level, thickness of slab and stiffness of shear stud on fire response of composite girders. Results from experimental and numerical analysis indicate that the composite girder subjected to flexural loading experience failure through flexural yielding mode, while the girders under shear loading, fail through in shear web buckling mode. Further, results from parametric studies clearly infer that shear limit state can govern the response of fire exposed composite girders under certain loading configuration and fire scenario.

Keywords: Composite girders, finite element analysis, fire resistance tests, shear, instability, composite action

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2.0 INTRODUCTION

When exposed to fire, composite girders (i.e. comprising of steel girder-concrete slab assembly) experience loss of load carrying capacity and stiffness due to temperature-induced degradation in strength and modulus properties of steel. As a result, these girders can be vulnerable to various failure modes such as temperature-induced large deflections, lateral torsional buckling, and flange/web local buckling. Recent studies have shown composite girders, under high shear loading, to be highly susceptible to shear web buckling especially when subjected to fire exposure [1-4]. Despite this experimental and numerical evidence, current fire design provisions only account for flexural limit state and do not specifically consider shear effects in evaluating failure of fire exposed composite girders. This approach of designing for flexural limit state although valid for most loading scenarios, may not be representative in certain situations where shear forces in girders are dominant, or shear capacity degrades at a rapid pace with fire exposure time. Hence, in order to achieve a realistic fire response evaluation, all possible failure modes need to be checked when evaluating fire resistance of composite girders.

A review of relevant research studies indicates that majority of previous experimental and numerical programs focused on flexural response of composite girders at ambient and fire conditions [3, 5-8]. For instance, Aziz et al. [3] undertook fire resistance experiments on three fully composite girders subjected to gravity loading. The main objective of these experiments was to evaluate the flexural capacity of one hot-rolled girder and two built-up plate girders subjected to standard fire conditions. The tested girders were simply supported and subjected to single point load at mid-span. Results in there fire tests indicated that composite girders subjected to flexural loading can experience failure in about 35-45 min of standard fire exposure. The time to failure

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and mode of failure in tested fire exposed composite girders was highly influenced by web slenderness of girder, and spacing of stiffeners. The authors reported that composite girders can fail through flexural yielding when web slenderness is around 50; however failure mode changes to web shear buckling when web slenderness exceed 100 (specifically in built-up plate girders).

Zhao and Kruppa carried out fire tests to evaluate the flexural behavior of fire exposed continuous composite girders [6]. The tested girders, comprising of steel section (girder) underneath concrete slab, had three supports (two at ends and one at center of girder) and subjected to two-point loading at each span. Zhao and Kruppa reported that although the tested composite girders failed in flexure, webs in these girders experienced signs of temperature-induced local buckling at the interior support due to development of large reaction force at interior support (resulting from high shear forces).

In a recent study, Naser [8] carried out fire experiments on compact (class 1) W-shaped hot-rolled composite girders (with full and partial composite action) subjected to dominant flexural and shear loading. Results of this study indicate that fire-exposed composite girders are highly susceptible to shear failure. This is due to the fact that webs in W-shaped sections are usually thinner (slender) than flanges. Also, since webs have larger surface area than flanges and are often exposed to fire from two sides, webs can be exposed to higher thermal loading than flanges. As a result, strength properties of steel in web can degrade at a higher rate than that in flanges (i.e. shear capacity of steel girders can degrade faster than flexural capacity).

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Despite findings in above studies, current fire design provisions continue to derive failure in fire-exposed composite girders based on flexural limit state only. To illustrate the critical nature of shear loading on fire exposed composite girders, this paper presents results from numerical studies on the fire response of composite girders subjected to combined effects of high flexural and shear loading. A newly developed finite element based numerical model is applied to evaluate the effects of initial geometric imperfections, load level, thickness of slab and stiffness of shear stud on the behavior of fire exposed composite girders.

3.0 NUMERICAL MODEL

To model the response of composite girders subjected to combined effects of fire exposure and high shear loading, a finite element based numerical model was developed in ANSYS [9]. For tracing a realistic fire response of girders, several governing parameters such as geometric and material nonlinearities, temperature-dependent material properties and various failure limit states were accounted for. Details of analysis procedure and model development including discretization, material properties, and various failure limit states are presented in the following sections.

3.1 Analysis procedure

Fire resistance analysis is generally carried out through two stages of analysis, namely thermal and structural analysis and each stage of analysis is composed of several time-steps. In thermal analysis, cross-sectional temperature distribution in a structural member is generated as a function of fire exposure time. The output of thermal analysis, i.e., nodal temperatures, is then applied as an input (i.e., thermal body load) to the structural model where a transient stress (structural) analysis is carried out. The structural analysis generates stresses, strains and

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deformations resulting from combined effect of thermal and structural loading. These steps, associated with fire resistance analysis of structural members are illustrated through a flowchart shown in Fig. 1. It should be noted that more details on analysis procedure can be found elsewhere [8].

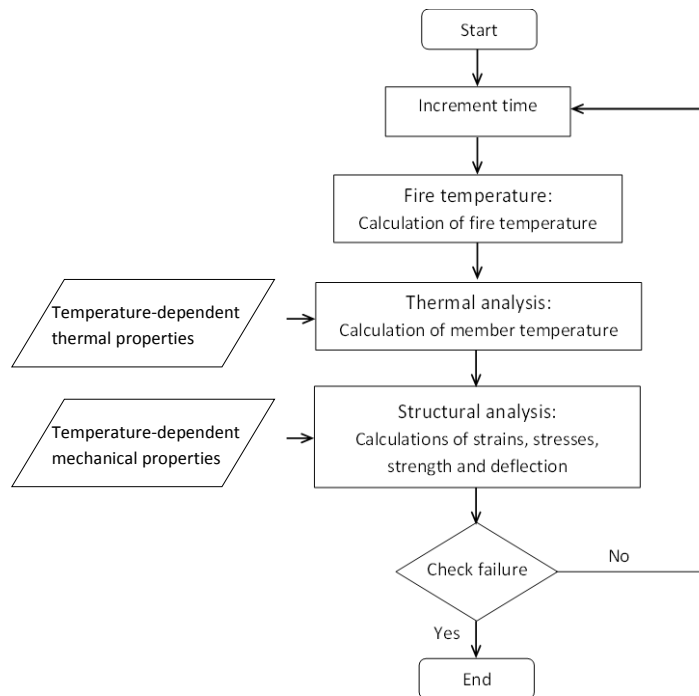


Fig. 1 Flowchart for fire resistance analysis of structural members

3.2 Girder discretization

For the analysis, the developed finite element model has the geometry of a typical composite girder comprising of a W-shape steel section (girder/beam) attached to concrete slab. In order to simulate the thermal response of a composite girder subjected to a typical fire scenario, the composite girder is discretized with thermal elements available in ANSYS elemental library. These elements are SOLID70, SHELL131, LINK33 and SURF152.

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SHELL131 is a layered shell element used to simulate the steel girder and has in-plane and through-thickness thermal conduction capability. SOLID70 is a cubic element with conduction capability and is used to discretize the concrete slab. LINK33 is a uniaxial element with the ability to conduct heat between its nodes and is used to simulate steel reinforcement embedded in the concrete slab. SURF152 is a surface element capable of simulating conduction, convection and radiation. This element is overlaid on top of SHELL131 and SOLID70 elements to simulate transfer of heat through different mechanisms from fire source to the composite girder in order to obtain nodal temperature. Once nodal temperatures are generated, these temperatures are input into the structural analysis.

In the second stage of analysis, the composite girder is discretized with suitable structural elements, namely SHELL181, SOLID65, LINK8, BEAM188, COMBIN14, COMBIN39, CONTA173 and TARGE170. SHELL181 is a shell element specifically formulated to capture local buckling of flanges and web and is used to discretize steel girder. SOLID65 is used to discretize concrete slab since this element is capable of accounting for cracking and crushing of concrete. LINK8 is used to simulate reinforcing steel embedded in concrete slab and COMBIN14 (a spring element) is used to model the bond-slip behavior between steel reinforcement and surrounding concrete.

BEAM188 element is used to simulate shear stud and the bond-slip action at the interface between shear studs and concrete slab was simulated using COMBIN39 elements. Furthermore, to account for composite action between concrete slab and the top flange of steel girder, nonlinear surface-to-surface contact pair elements (CONTA174 and TARGE170) are used. This contact pair

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can be fully bonded to simulate full composite action between the concrete slab and steel girder or it can be partially bonded to account for the slip that occurs between the concrete slab and steel girder in case of partial composite action. Further details on simulation techniques can be found elsewhere [1, 2, 8]

3.3 Constitutive laws and temperature-dependent material properties

In order to effectively trace the response of composite girders under fire conditions, high temperature material properties of various constituent materials namely, structural steel, concrete, steel reinforcement, and shear studs are to be input in the developed numerical model. As a result, high-temperature thermal and mechanical properties of steel and concrete specified in Eurocodes 3 and 2 [10, 11] are used in numerical analysis.

To simulate the behavior of structural and reinforcing steel in compression and tension, multilinear stress-strain relationships with Von-Mises plasticity yielding criterion and isotropic hardening plasticity model based on Eurocode relations are used in fire resistance analysis. Furthermore, the plastic behavior of concrete is simulated using Williams and Warnke constitutive material model which takes into account the spread of plasticity of concrete in both compression and tension regimes [12]. The compressive plastic behavior of concrete is defined using isotropic multi-linear compressive stress–strain curves that vary with temperature and the tensile behavior of concrete is modeled using a trilinear model. In this model, the concrete tensile strength is taken as $0.62\sqrt{f'_c}$; where f'_c is the compressive strength of concrete. Once the concrete reaches its tensile stress, a tensile stiffness multiplier of 0.6 is used to simulate a sudden drop of the tensile stress to 60% of the initial rupture stress [9].

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It should be noted that the horizontal shear force-slip that develops between shear studs and concrete slab is simulated using force-slip relation based on a nonlinear constitutive relationship proposed by Ollgaard et al. [13].

$$V_h = Q_u \left[1 - e^{-4.75S} \right]$$

where V_h is the shear force, Q_u is the strength of the studs calculated as $Q_u = 0.43A_s\sqrt{E_c f'_c} \leq 0.7A_s f_u$; A_s , E_c , f'_c and f_u are cross sectional area of the shear studs, elastic modulus of the concrete taken as $4600\sqrt{f'_c}$ (in MPa), compressive strength of the concrete, and ultimate strength of the studs taken as 45 and 420 MPa, respectively. S is slip and was set to 1.27 mm [14].

3.4 Failure limit states

The failure of a composite girder, under fire conditions can occur in different modes. Thus, the evaluation of realistic failure requires applying all possible limit states, including thermal (limiting temperature), flexural, shear, local buckling and deflection, in evaluating failure of structural member at each time step. Hence, failure is said to occur once any of these limiting states is exceeded.

For example, moment and shear capacity at each time step are evaluated utilizing internal bending and shear stresses generated from structural analysis. These stresses, generated at distinct elements, are integrated across the height of the section. Once the stresses across the height of the section are obtained, these stresses are input into an ANSYS Parametric Design Language (APDL) supplementary sub-routine. This sub-routine uses generated stresses to calculate associated

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sectional moment and shear capacity. To maintain equilibrium, the calculated moment and shear capacities are then compared against the bending moment and shear force due to applied loading level. Once the applied loading level exceeds that of the moment and/or shear capacity, the structural member is said to fail.

Similarly, local buckling limit state is also checked at each time step by comparing web and flange slenderness to that of the temperature-dependent slenderness limits. For instance, slenderness of flanges and web is checked against temperature-dependent flexural and shear slenderness limits at each time-step using the above mentioned supplementary sub-routine. Once the sectional slenderness exceeds the degraded compactness or non-compactness slenderness limit (λ_p or λ_r), local buckling is said to occur and sectional capacity (i.e., flexural and/or shear) is adjusted to account for the loss arising from local buckling.

Finally, a deflection limit state is also applied to evaluate failure of fire exposed structural members. When the structural member 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 structural member, respectively, the structural member is said to attain failure [15].

4.0 FIRE RESISTANCE EXPERIMENTS

To generate needed data for validating the above numerical model in predicting fire response of composite girders, fire tests were conducted on three composite girders. In these tests, the girders were tested to failure by subjecting them to combined effects of structural loading and fire exposure.

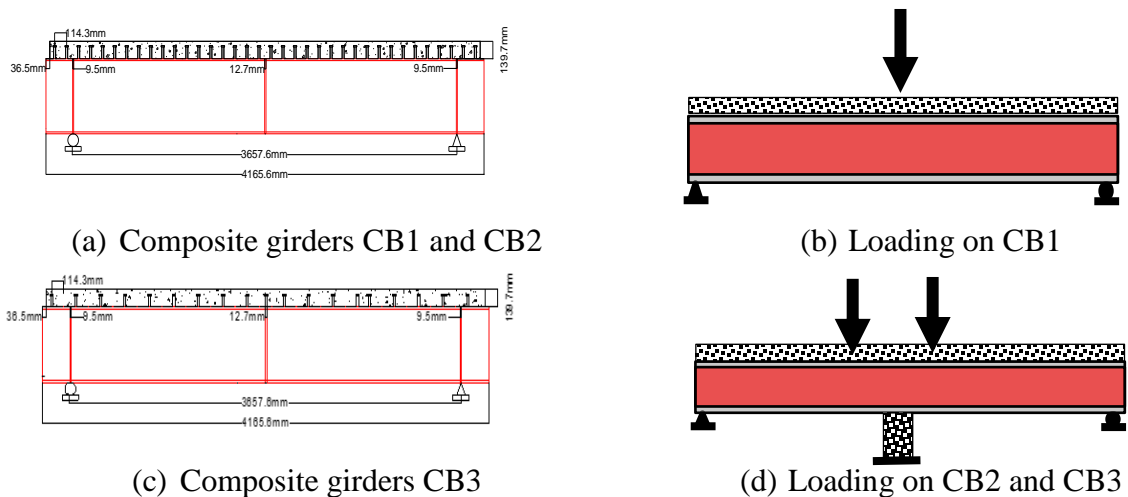
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4.1 Test Specimens

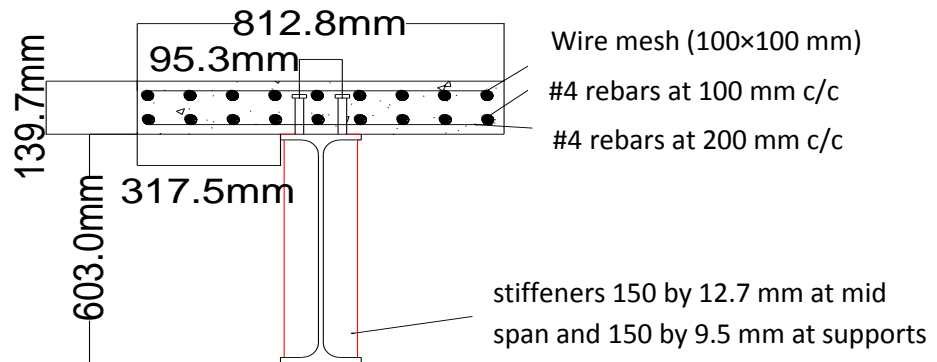
The three composite girders, designated as CB1, CB2, and CB3, were designed according to AISC specifications [16]. The steel girders, made of W24×62 standard hot-rolled section, were fabricated using A572 Grade 345 steel. The concrete slab, cast along the full length of the steel girder, was made of normal strength concrete of compressive strength of 45 MPa and had a depth and width of 140 and 815 mm, respectively.

The first composite girder (CB1), was subjected to flexural loading and exposed to ASTM E119 standard fire, while the other two girders (CB2 and CB3) were subjected to high shear loading and a similar fire exposure to that of applied to CB1. Composite girders CB1 and CB2 were designed to have full composite action between steel girder and the concrete slab, and thus were provided with two rows of 19 mm diameter shear studs placed at 115 mm. On the other hand, composite girder CB3 was provided with two rows of 19 mm diameter shear studs placed at 230 mm to achieve partial (50%) composite action. Figure 2 shows further details of tested composite girders as well as loading set-up and end boundary conditions.



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(e) Cross section of composite girders

Fig. 2 Longitudinal and traverse sections for composite girders

4.2 Test Set-up

The fire resistance tests were carried out at the structural fire testing facility at Michigan State University. This testing facility "fire furnace" is made of a steel framework supported by four steel columns, with the furnace chamber inside the framework. This chamber is 2.44 m wide, 3.05 m long, and 1.78 m high and can produce a maximum heat energy of 2.5 MW using six gas burners located within the furnace. During the course of fire test, the gas supply is manually adjusted such that the furnace temperatures follow the ASTM E119 standard fire curve [17]. The average temperature inside of the furnace were monitored through six type-K Chromel-alumel thermocouples mounted on the walls of the furnace as per ASTM E119 specifications.

Composite girder (CB1) was tested under flexural loading and had simply supported boundary conditions (i.e. CB1 was subjected to one-point load applied at mid-span of the girder). In order to simulate high shear forces on composite girders (CB2 and CB3) during fire exposure, an intermediate support was placed at the mid-span section of these girders, such that high shear loading can be applied on the sides of the intermediate support using two hydraulic actuators (see

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Fig. 2d). This intermediate support was made of reinforced concrete column with a square cross section (204×204 mm). This column was casted with a special concrete mix, made of high strength concrete containing polypropylene fibers, to avoid any possible fire induced spalling during fire test. During fire tests, this column was also insulated with 50 mm thick insulation to limit temperature rise and avoid possible elongation (or spalling) in column.

4.3 Test Conditions and Procedure

During fabrication, composite girders were instrumented with a number of thermocouples, and displacement transducers to monitor thermal and mechanical response during and post fire exposure. Temperatures in steel girder were measured using 0.91 mm thick Type-K Chromel-alumel thermocouples installed on the lower and upper flanges, as well as on four vertical locations along the height of the web of each girder, at quarter and mid-span locations. Additional thermocouples were also mounted on shear studs, at mid-depth and surface of concrete slab.

In order to measure vertical deflections and axial deformations, vertically and horizontally oriented linear variable displacement transducers (LVDT) were attached below loading points and at end supports. Out-of-plane displacement of the web was also measured through a well-insulated "L-shape" stiff threaded steel rod which was attached to the center of the web panel and extended horizontally (i.e. perpendicular to girder). This steel rod was then extended vertically to pass through a special opening in the furnace lid.

Prior to fire tests, a predefined vertical load was applied using hydraulic actuators and this load was kept constant throughout the fire test. This predefined load was 33-40% of flexural and shear capacity of the tested girders. For instance, in the first test, composite girder CB1 was

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subjected to a single point load equivalent to 40% of its room temperature flexural capacity, which translates to 27% of its shear capacity. However, composite girders CB2, and CB3 were subjected to two point loads placed at 430 mm from mid-span section through a different set of hydraulic actuators. The applied loading on composite girders CB2, and CB3 was equivalent to 5% of flexural capacity and 33% of shear capacity of these girders as evaluated based on AISC provisions [16]. In all three fire tests, a fire exposure following the ASTM E119 time-temperature curve was simulated and the tests were terminated when the girders could no longer carry the applied loading [17, 19].

5.0 MODEL VALIDATION

Data generated in the fire tests is utilized to validate the above developed numerical model in tracing fire response of composite girders subjected to flexural and shear loading. In this analysis, the developed finite element model has the geometry and material properties of the tested composite girders and was subjected to similar loading and fire conditions as that applied in the fire tests. Thus, a composite steel girder made of hot-rolled standard steel section of W24×62 shape is selected. In order to validate the developed finite element model, various output parameters generated in the analysis, namely temperature and deflections, in the composite girders are compared against the measured data in fire tests.

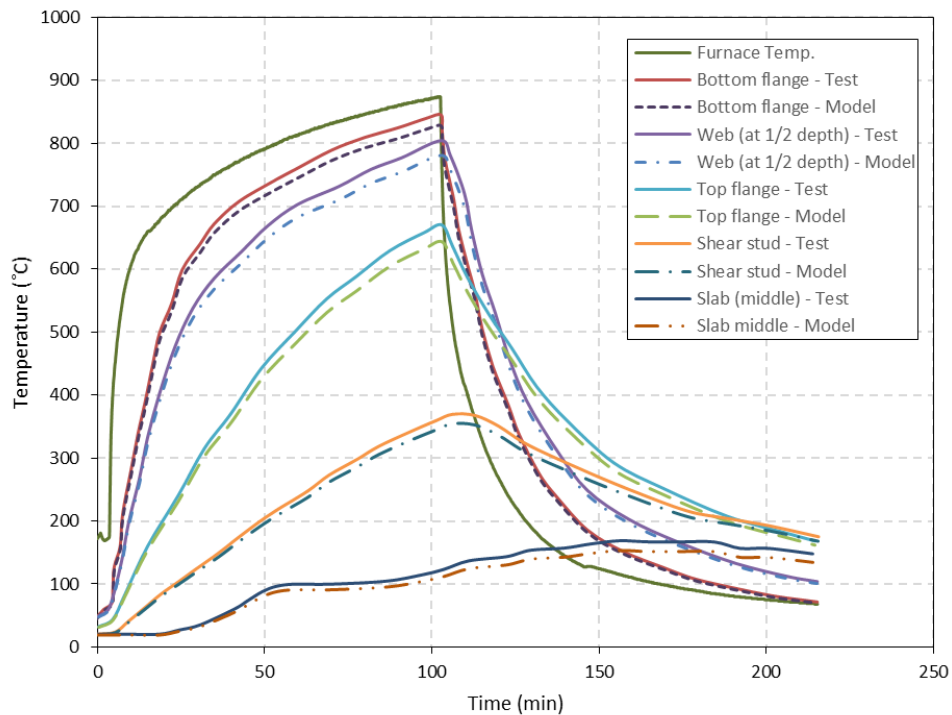
5.1.1 Thermal Response

The three tested composite girders had similar cross-sectional geometry, material properties and were exposed to the same fire exposure scenario (i.e. ASTM E119), and therefore all three girders experienced similar temperature rise under fire exposure. For validating thermal predictions in girders, measured cross-sectional temperatures at various points in web, flanges,

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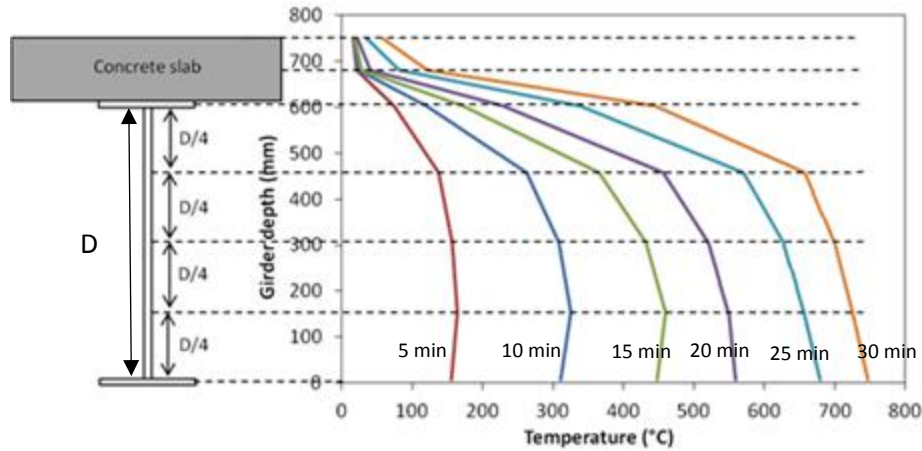
shear studs, and concrete slab were compared against predicted temperatures from finite element analysis as shown in Fig. 3a [3, 8]. In general, temperatures in steel section (girder) rise at a much rapid pace than that in concrete slab and this is mainly due to the heat-sink effect of concrete slab, facilitated by higher heat capacity and lower thermal conductivity of concrete. Towards the end of fire exposure, average temperature in web and bottom flange was in the range of 700-850°C, however temperature in shear studs and mid-depth of concrete slab remained well below 200°C.



(a) Comparison of predicted and measured cross-sectional temperatures

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(b) Thermal gradient along the depth of composite girder [3]

Fig. 3 Thermal response of composite girder CB1

The high variation in temperatures between bottom flange and concrete slab often leads to high thermal gradients across the depth of the composite section as shown in Fig. 3b. These thermal gradients increase with fire exposure time due to the continuous temperature rise in bottom flange and web. Such gradients induce significant thermal stresses, which in turn influence the structural response of composite girder.

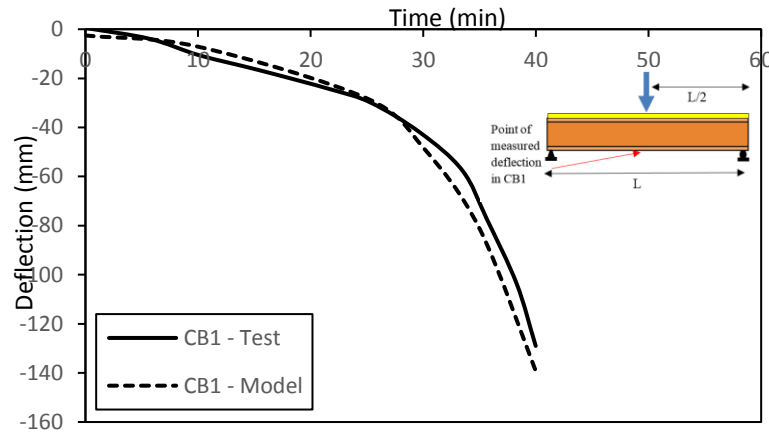
5.1.2 Structural Response

In order to validate the structural response predicted from the developed finite element model, predicted and measured vertical deflections for fire-tested composite girders are compared in Fig. 4. This figure shows that vertical deflection in CB1, which was taken at mid-span section of composite girder (see Fig. 4a), gradually increases especially during the early stage of fire. The mid-span deflection continues to increase (between 10 and 25 min) due to degradation of strength and modulus properties of the steel. After 30 minutes into fire exposure, the mid-span deflection increases at a rapid pace due to spread of plasticity in the bottom flange, and high temperature creep effects, leading to formation of plastic hinge at mid-span. The girder is said to attain failure

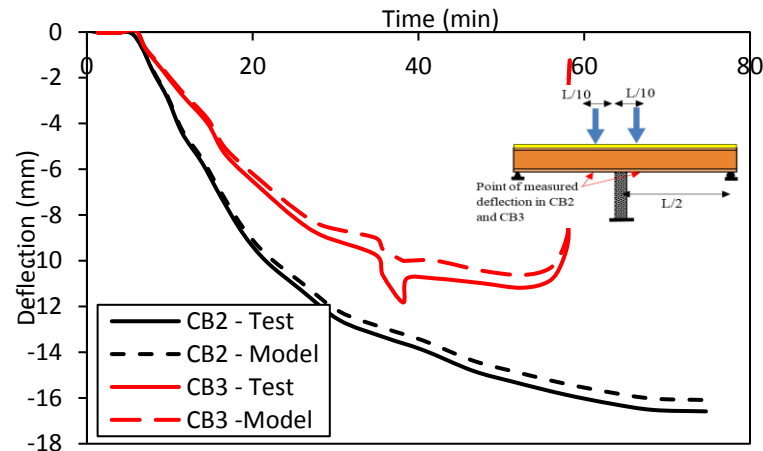
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at 40 min when mid-span deflection exceeds deflection limit ($span/30$) in BS-476 standard as the girder cannot sustain applied loading [15].



(a) Mid-span deflection for composite girder CB1



(b) Vertical deflection for composite girders CB2 and CB3

Fig. 4 Comparison of predicted and measured deflections in girders CB1, CB2 and CB3

In the case of composite girders CB2 and CB3, vertical deflection was measured below loading points (see Fig. 4b) and deflection in these girders gradually increased throughout fire exposure time. Although the vertical deflection in girder CB3 (designed with partial composite action) is slightly larger than that in CB2 (designed with full composite action), magnitude of

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deflection of CB2 and CB3 remains very small as compared to mid-span deflection in CB1 (which reached 140 mm). It is worth noting that the maximum deflection in CB2 and CB3 was 11 and 17 mm, respectively (which corresponds to 7 and 13% of that of the deflection limit criteria ($span/30$) [15]).

In general, response of girders CB1, CB2 and CB3 varied due to the different loading type adopted in testing of these girders and its impact on resistance mechanism developed within each girder. For instance, composite girder CB1 (tested under flexural loading) experienced large mid-span deflections, while composite girders CB2 and CB3 experienced much lesser amount of deflection since the structural loading was applied very close to the intermediate support (to simulate high shear loading). It is clear that failure in composite girders CB2 and CB3 occurs upon attaining their sectional capacity and not due to exceeding deflection limit state as in the case of CB1. Figure 4 shows that predictions from finite element model agrees well with that of the measured test data and these comparisons infer that the above developed finite element model is capable of predicting response of fire exposed composite girders subjected to flexural or shear loading.

6.0 PARAMETRIC STUDY

The above validated finite element model was applied to evaluate the effect of critical parameters on the structural response of fire exposed composite girders subjected to high shear loading. These parameters include initial geometric imperfections, load level, thickness of slab and stiffness of shear stud. The parametric studies were carried out on typical girders having similar geometry, material properties, loading and boundary conditions as that of tested composite girder

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CB2. It is worth noting that all tested girders had sufficient flexural capacity and as such girders failed due to shear effects [8].

6.1 Effect of initial geometric imperfections

Due to the complex nature of fabrication process of composite girders (specifically steel sections), fabricated steel sections often have initial geometric imperfections. Thus, actual geometric dimensions are usually different than the nominal values listed in standardized design manuals and listings. To quantify the effect of sectional stability on response of fire exposed composite girders, the pattern of initial geometric imperfections is often chosen to be the worst case scenario in order to account for instability effects. For example, ASTM A6/A6M (2011) specifies an imperfection magnitude of $L/960$ (where L is the span length) to be applied to the geometry of the structural member [19]. To account for the effect of initial geometric imperfections on the structural behavior of fire-exposed girders, the geometry of composite girder in the finite element model is updated using various scaled deformations. The scaled deformations ranged from $L/10$, $L/100$, $L/1000$, $L/5000$ to $L/10000$, where L is the total length (span) of the girder. The procedure of applying geometric imperfections in the analysis is described elsewhere [8, 9].

Figures 5 and 6 show the predicted response of girders with various initial imperfections, together with their deformed shape at failure. It is worth noting that level of geometric imperfections does not significantly affect vertical deflection in fire exposed composite girders. However, the level of initial geometric imperfections can significantly affect deformed shape (and failure mode) of girders under simultaneous high shear loading and fire exposure. For instance, composite girders with initial imperfections of $L/100$ and $L/1000$ provide the closest response as

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compared with the experimentally tested girder CB2 which was assumed to have a geometric imperfection level of $L/960$ (see Fig. 10f). Thus, applying initial imperfections of $L/100$ and $L/1000$ can accurately capture buckling behavior of web and produce deformation close to those experienced in fire tests.

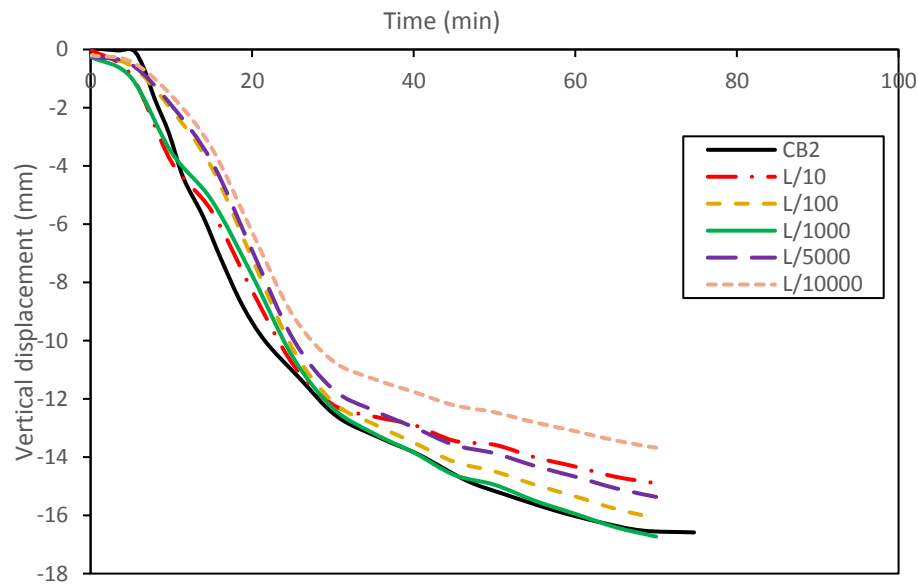
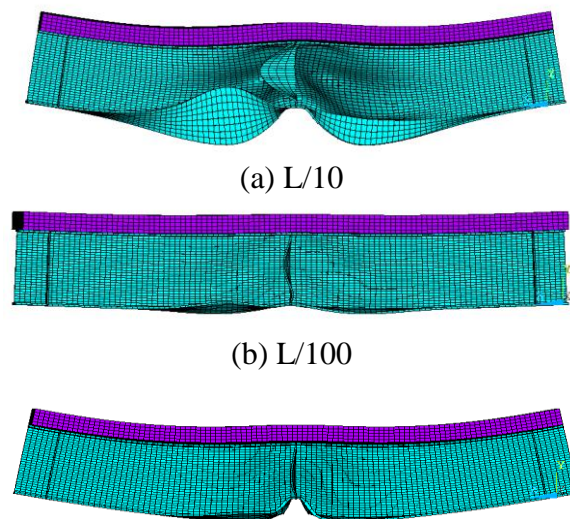


Figure 5 Deflection response of composite girders with different magnitude of initial imperfections



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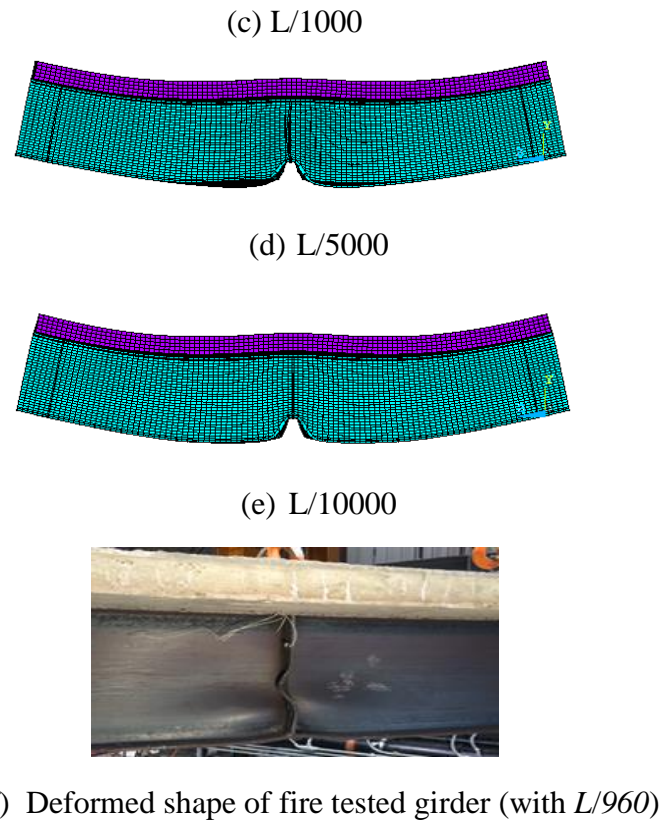


Figure 6 Deformed shape at failure of composite girders with different initial imperfections

6.2 Effect of load level

The load level (LL) applied on girder can have significant influence on the response of fire exposed composite girders. For example, heavily loaded composite girders generate higher internal stresses to counter-balance (resist) the applied loading. Thus, a composite girder subjected to higher level of loading can reach plastification stage (i.e. yield limit of steel) much earlier than a girder loaded with lower load level, especially under fire conditions when strength properties degrade rapidly.

The load level, corresponding to shear limit state, can be defined as the ratio of the maximum shear force (V_{max}) induced due to the loading present during fire exposure to the shear capacity ($V_{capacity}$) of the composite girder at room (ambient) temperature, i.e.

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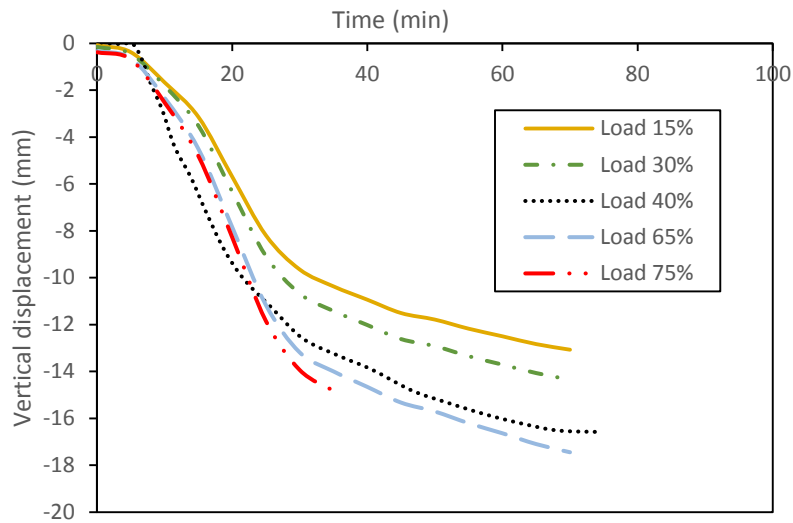
$$LL = \frac{V_{\max}}{V_{\text{capacity}}} \times 100\%$$

In current codes of practice, fire resistance in structural members is generally evaluated based on a load level (load ratio) of 40-50%. This is based on the fact that structural members at room temperature are designed for various load combinations and since fire is a rare even, the probability of all such loading combinations to be present during fire is low [10]. To account for the effect of load level on the shear response of fire-exposed composite girders, various load levels ranging from 15, 30, 40, 65, and 75% of shear capacity of girders are studied herein.

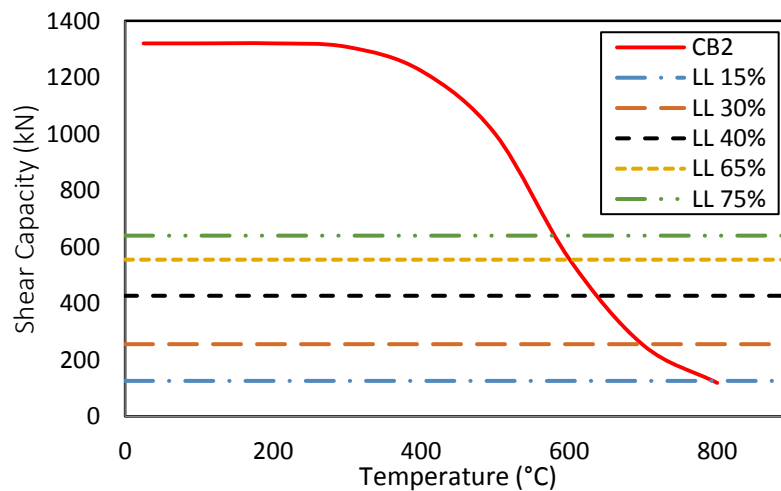
To illustrate the effect of varying load level on shear response of fire-exposed girders, Fig. 7a shows a comparison between vertical deflection in girders loaded with 15, 30, 40, 65, and 75% of their shear capacity. This response plot shows that higher load levels increase deflections leading to early failure of composite girders. In order to further examine the effect of varying load level on shear response of composite girders, degrading shear capacity of composite girder CB2 is plotted as a function of fire exposure time in Fig. 7b. It can be seen from this figure that high loading levels cause failure at lower temperatures (which corresponds to earlier failure times). For example, composite girders loaded with 15, 30, 40, 65, and 75% of their shear capacity fail when average web temperature reaches 800, 700, 640, 600 and 580°C, respectively.

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(a) Vertical deflection in composite girders loaded with load level of 15, 30, 40, 65 and 75% of shear capacity



(b) Degradation of shear capacity with fire exposure time

Figure 7 Response of fire exposed composite girders subjected to varying loading levels

6.3 Effect of slab thickness

In composite girders, presence of concrete slab enhances load bearing capacity (both flexural and shear) and also provides additional stiffness and bracing to fire exposed composite

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girders [2, 7, 8, 20, 21]. For example, Fig. 8 shows a comparison of deformed shape of an isolated steel girder and composite girder subjected to the same load level and fire exposure. It can be seen that presence of concrete slab provides lateral restraint to steel girder and as such concrete slab prevents occurrence of compressive local buckling of flange and top portion of web (or global buckling, i.e. lateral torsional buckling). Further, previous studies have shown that composite girders with relatively thicker concrete slabs can have larger shear capacity than that in composite girders with thinner slabs [7, 20, 21]. Thus, in order to quantify the effect of concrete slab thickness on shear response of fire-exposed composite girders, a parametric study was carried out by varying thickness of concrete slab as 50, 100, 200, 250, and 350 mm, on the same steel shape (girder).

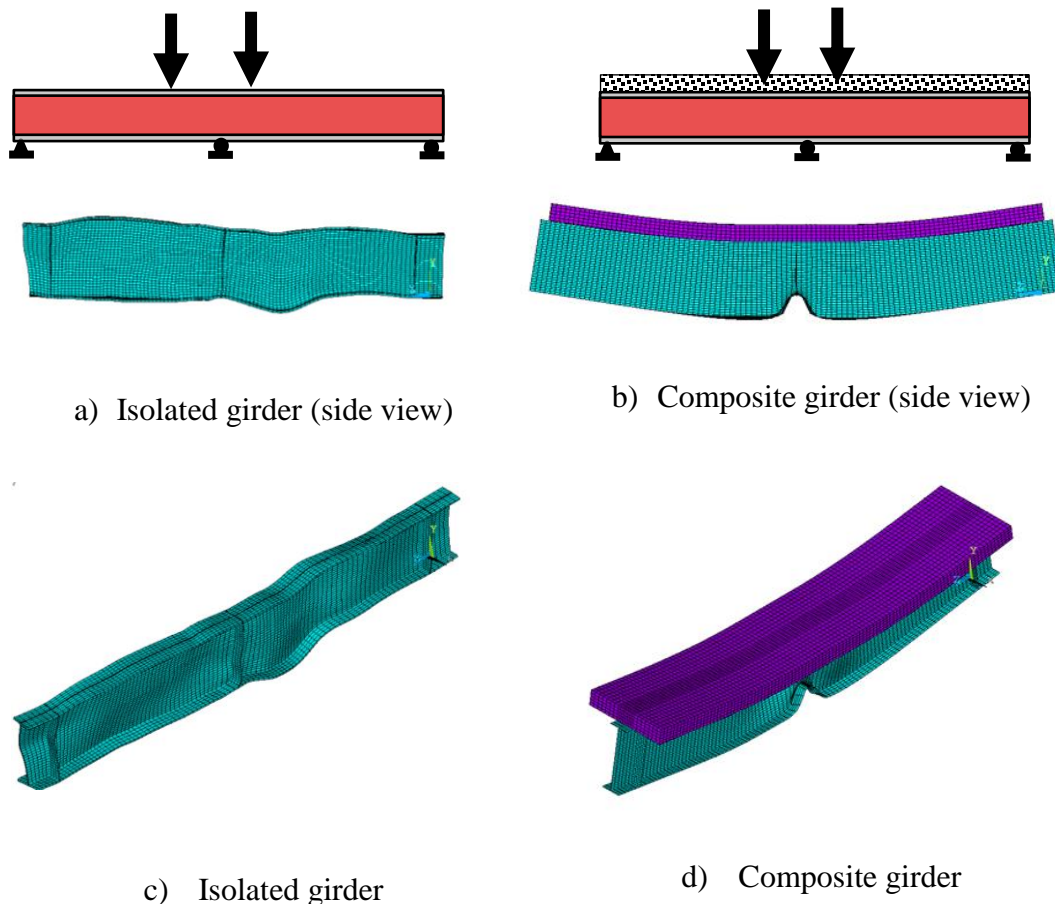
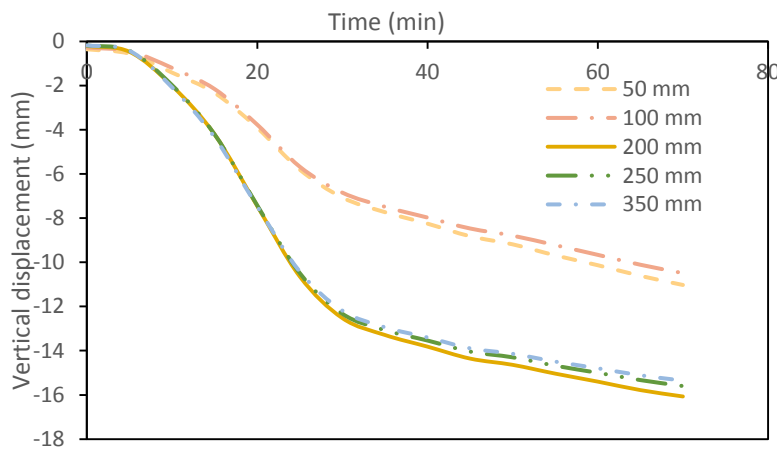


Figure 8 Effect of concrete slab on failure mode of fire-exposed isolated and composite girder

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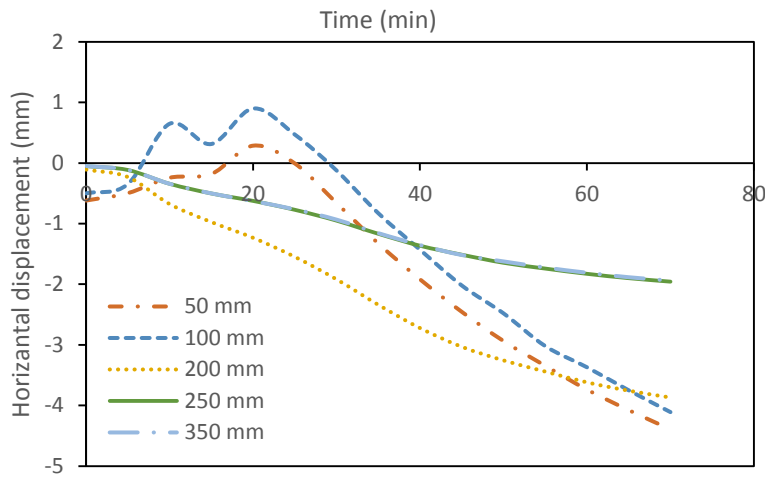
Figures 9a and 9b show that the overall structural response of composite girders with varying concrete slab thickness is a function of the interaction of vertical and horizontal displacement of the girder. The data in these figures illustrate that horizontal web displacement in composite girders, with relatively thin concrete slab thickness (of 50 and 100 mm), undergo a different response than that of the webs in composite girders with thicker slabs. In composite girders with thinner slabs, web can translate with an "in-and-out of plane" pattern due to the overall flexibility of the composite girder. Hence, it can be inferred that thicker concrete slabs (of more than 100 mm) can effectively brace and laterally restraint fire exposed composite girders, to good extent.



(a) Vertical deflection

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(b) Horizontal web-displacement

Figure 9 Response of composite girders with varying concrete slab thickness

6.4 Effect of shear stud stiffness

In a composite beam-slab assembly, shear studs (shear connectors) play a key role in achieving certain level of composite action between the steel girder and concrete slab. This is due to the fact that transfer of forces between steel girder and concrete slab is facilitated through shear studs. Although the number of shear studs dictates the level of composite action developed [7, 20, 21]), the rigidity (i.e., stiffness) of shear studs can affect the distribution of shear flow which in turn affect the amount of force being transferred compositely between steel girder and concrete slab [8, 22]. In a notable study, Oehlers and Coughan [22] have shown, through pull-out tests, that stiffer shear studs can resist higher level of shear flow without bending, breaking or pulling out when compared to shear studs with lower stiffness.

A typical shear stud used in current practice has a stiffness (K) of 125.2 kN/mm and this stiffness is a function of maximum shear load, diameter of shear stud and compressive strength of concrete. This shear stud stiffness (K) can be evaluated as

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$$K = \frac{P}{d_{sc}(\alpha - 0.0017f'_c)} \quad (\text{Eq. 1})$$

where, P is the shear load, d_{sc} is the diameter of shank, f'_c is the compressive strength of concrete, and α is a constant taken as 0.08 [22].

In order to quantify the effect of varying shear stud stiffness on response of fire exposed composite girders, stiffness of shear studs was varied from $\frac{1}{4}$, $\frac{1}{2}$, 1, 2 to 5 times the amount of actual stiffness in a typical shear stud. It should be noted that in all cases presented herein, composite girders are assumed to have full composite action developed between steel girder and concrete slab through providing sufficient number of shear studs [8].

Figure 10 shows that stiffness of shear studs can affect deflection response of composite girders. This figure also shows that the role of shear studs start to be apparent after 10-20 min of fire exposure, when temperature rise in steel section reaches 300-400°C. At this temperature range, steel section starts to lose some of its initial strength and stiffness and more forces are to be transferred into the cooler concrete slab (to maintain stability and equilibrium). Thus, composite girders with stiffer shear stud can transfer more forces from fire-weakened steel girder to the cooler slab and hence perform better than composite girders with flexible studs.

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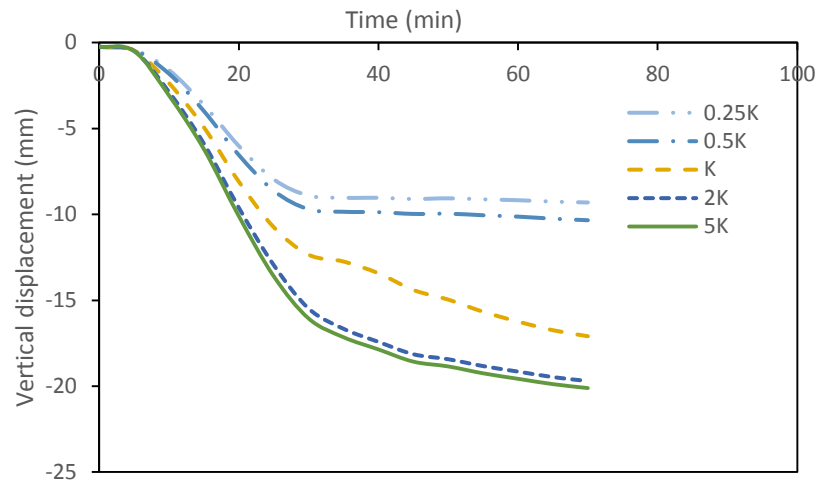


Figure 10 Vertical deflection of fully composite girders with varying shear stud stiffness

7.0 CONCLUSIONS

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

1. Under fire exposure, due to higher slenderness of web, temperature in web of steel sections of composite girders rises more rapidly than that in flanges. Hence, shear capacity in a steel girder degrades at a faster pace than flexural capacity and this can lead to failure of the girder under shear limit state prior to attaining flexural limit state.
2. Composite girders loaded with high shear forces (and exposed to fire) do not undergo large deflections or rotations. These girders fail due to temperature-induced web shear buckling which often occur before reaching deflection limit criteria, currently used in most building codes and standards.

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3. The critical parameters that govern the fire resistance composite girders are type of loading (shear/flexural), initial geometric imperfections of steel section, load level, thickness of slab and stiffness of shear stud.
4. The presence of concrete slabs of more than 100 mm thickness can limit adverse effects of temperature-induced web local buckling at least in fire exposed composite girders.

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9.0 REFERENCES

- [1] Kodur, V.K.R. and Naser, M.Z. 2014. "Effect of Local Instability on Capacity of Steel Beams Exposed to Fire," *Journal of Constructional Steel Research*, 111: 31–42.
- [2] Naser, M.Z. and Kodur, V.K.R. 2016. "Factors Governing onset of Local Instabilities in Fire Exposed Steel Beams," *Journal of Thin-Walled Structures*, 98: 48-57.
- [3] Aziz, E., Kodur, V., Glassman, J. and Garlock, M. 2015. "Behavior of steel bridge girders under fire conditions," *Journal of Constructional Steel Research*, 106: 11-22.
- [4] Kodur, V.K.R. and Naser, M.Z. 2013. "Effect of Shear on Fire Response of Steel Beams," *Journal of Constructional Steel Research*, 97: 48-58.

Please cite this paper as:

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[5] Basler, K., Yen, B., Mueller, J. and Thürlimann, B. 1960. "Web Buckling Tests on Welded Plate Girders," *Welding Research Council Bulletin*, 64.

[6] Zhao, B. and Kruppa, J. 1993. "Fire resistance of composite slabs with profiled steel sheet and of composite steel concrete beams Part 2: Composite beams," *Centre technique industriel de la construction métallique*.

[7] Vasdravellis, G. and Uy, B. 2014. "Shear Strength and Moment-Shear Interaction in Steel-Concrete Composite Beams," *J. Struct. Eng. ASCE*, 140.

[8] Naser, M. Z. 2016. "Response of Steel and Composite Beams Subjected to Combined Shear and Fire Loading," PhD. Dissertation. Michigan State University, East Lansing, US.

[9] ANSYS metaphysics Version 14. 2013. ANSYS Inc. Canonsburg, PA, USA.

[10] European Committee for Standardization (CEN). 2005. "Eurocode 3: Design of steel structures—Part 1–2: General structural rules—Structural fire design," EN 1992-1-2, Brussels, Belgium.

[11] European Committee for Standardization (CEN). 2004. "Eurocode 2: Design of concrete structures—Part 1–2: General structural rules—Structural fire design," EN 1992-1-2, Brussels, Belgium.

[12] Willam, K. and Warnke, E. 1975. "Constitutive Model for the Triaxial Behavior of Concrete," *In Proceedings of the Concrete Structure Subjected to Triaxial Stresses*, International Association for Bridge and Structural Engineering, Bergamo, Italy: 1–30.

Please cite this paper as:

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[13] Ollgaard, J.G., Slutter, R.G. and Fisher, J.W. 1971. “Shear strength of stud connectors in lightweight and normal weight concrete.” *Eng J AISC*, 8: 55-64.

[14] Comite Euro-International du Beton (CEB-FIP). CEB-FIP model code 1990. Bulletin D’Information No. 213/214 (Concrete Structures), Lausanne, Switzerland.

[15] British Standard Institution, Fire Tests on Building Materials and Structures. Part 20. Method of Determination of Fire Resistance of Elements of Constructions, BS 476, 1987.

[16] AISC. 2011. Specification for structural steel buildings 360–11. American Institute of Steel Construction Inc.; Chicago, IL.

[17] ASTM E119. 2002. Standard test Methods for Fire Tests of Building Construction and Materials. ASTM international. West Conshohocken, PA.

[18] Naser, M.Z. and Kodur, V.K.R. 2016. “Comparative Behavior of Fire-Exposed Composite Girders Subjected to Flexural and Shear Loading,” *Proceedings of the Ninth International Conference on Structures in Fire*, Princeton, USA: 719-726.

[19] ASTM-A6/A6M. 2011. Standard specification for general requirements for rolled structural steel bars, plates, shapes, and sheet piling. American Society for Testing and Materials, West Conshohocken, PA.

[20] Nie, J., Xiao, Y. and Chen, L. 2004. “Experimental Studies on Shear Strength of Steel–Concrete Composite Beams,” *J. Struct. Eng.*, 130: 1206-12134.

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[21] Liang, Q., Uy, B., Bradford, M., and Ronagh, H. 2005. "Strength Analysis of Steel–Concrete Composite Beams in Combined Bending and Shear," *J. Struct. Eng.*, 131: 1593-1600.

[22] Oehlers, D. J. and Coughlan, C.G. 1986 "The shear stiffness of stud shear connections in composite beams," *Journal of Constructional Steel Research*, 6: 273-284.