Analysis of Steel-Concrete Composite Bridge Girders Under Fire Conditions

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***Abstract*— In recent years, bridge fires are becoming a growing concern due to rapid urbanization and increased ground transportation of hazardous materials. Due to high intensity of fires, substantial structural damage, even collapse of bridges occur which lead to large public and property loss. Steel-concrete composite girders are now becoming popular among bridge construction. Under fire conditions, steel-concrete composite bridges, steel girders are more vulnerable to fire as compared to piers and abutments. This is due to the high thermal conductivity of steel which results in rapid rise in temperature inside girders. Hence behaviour of girders under fire conditions is of critical concern from fire safety point of view. The objective of this work is to study the behaviour of steel-concrete composite bridge girders under fire. Finite element software ANSYS is used to perform the thermal and structural analysis.**

Keywords*— *Fire resistance, Composite action, Bridge fires, Thermal analysis, Structural analysis

I. INTRODUCTION

A. General

Bridges are a vital part of navigational systems for facilitating the flow of traffic over natural or constructed obstacles. Recent years have shown huge demand of bridge construction due to new trends in urbanization and increase in traffic demands. Since bridges form key elements in a highway transportation system, its failure means the failure of the entire route network [1]. Even though a lot of attention has been paid to understand and predict the effects on bridges by various accidental load events such as earthquake, wind, scour etc., fire load has been given very little consideration as proved by recent literature reviews. Fire in bridges can lead to long traffic disruption and significant economic losses. Further, a severe fire may lead to permanent damage or even collapse of the bridge. Crashing of fuel transporting trucks and burning of those highly flammable gases in the vicinity of the bridge is one of the most critical cause in many of bridge fire incidents. The fire thus produced is highly dangerous as compared to building fires and they spread in rapid directions with high heating pace. Such intense fires can pose a severe threat to structural members and can lead to collapse of structural members of a bridge. Recent trends shows huge demand in construction of composite steel concrete composite girders. Advantageous properties of both steel and concrete are effectively utilized in a composite bridge. Steel is widely used in bridge construction due to number of advantages steel possesses, including higher strength, ductility, and cost considerations. However, steel structural members exhibit lower fire resistance as compared to concrete members due to rapid rise in steel temperatures resulting from high thermal conductivity, low specific heat, and lower sectional mass of steel. This ultimately leads to reduced load carrying capacity under fire conditions. Thus composite bridge girders are vulnerable to fire induced collapse.

B. Steel-concrete composite bridge girders

A composite steel-concrete composite girder consists of precast reinforced concrete deck slab or precast pre-stressed concrete deck slab with I steel section as beam. The steel structure of a bridge is fixed to the concrete structure of the deck so that the steel and concrete act together, so reducing deflections and increasing strength. This is done using 'shear connectors' fixed to the steel beams and then embedded in the concrete. Steel–concrete composite beams are widely used buildings and bridges due to their capability in developing high flexural strength and stiffness. Unprotected structural steel sections, when subjected to fire, can have rather limited fire resistance due to the rapid rise of temperature in the member. This rapid rise in temperature is followed by a rapid loss in stiffness and strength. Fire resistance however can be significantly increased when steel elements interact with structural materials characterized by low thermal conductivity such as concrete. In recent years, there have been a number of analytical and finite element models developed for composite beams at both ambient and elevated temperatures.

A review of literature indicates that there is a lack of information on the fire performance of bridge girders, and this is mainly due to the fact that little attention has been paid to structural fire safety in bridges. This paper presents results from an analytical study on the fire performance of steel bridge girders.

II. OBJECTIVES

The main objective of this project work is:

To study the thermal and structural behavior of steel-concrete composite girders subjected to fire

III. METHODOLOGY

A. Modelling

A numerical study is carried out using the FEM computer program ANSYS to illustrate the response of a steel girder exposed to fire. For the analysis, a simply supported girder with a total span of 25.8m is taken. This bridge girder is generally comprised of different structural components, namely, girder, RC slab, shear connectors. For thermal and structural analyses, two sets of discretization models has been developed. The thermal-analysis results are imported to structural model and applied as thermal-body load on it uniformly along the girder span. High-temperature thermal and mechanical properties of steel and concrete have been incorporated in the analysis. ASTM E119 fire curve is given as fire load. Deflection limit state is adopted for defining failure, and the failure is said to occur when the deflection becomes span/20. Both heat-convection and radiation loads have been applied at the exposed surface areas of the solid element. Convection coefficient of $\alpha = 35 W/m^2\ ^{\circ}C$ is used in the thermal analysis under and this is based on Eurocode 1[European Committee for Standardization (CEN) 2002] recommendations. A Stefan-Boltzmann radiation constant of $5.67x10^{-8}\ W/m^2\ ^{\circ}C$ is applied in the thermal analysis.

B. Discretization for Thermal Analysis

For the discretization of the girder, slab, and stiffeners, SOLID70 elements were used. SOLID70 is a three-dimensional (3D) element with 3D thermal conduction capability and has eight nodes with a single degree of freedom, namely, temperature, at each node. This element is applicable to 3D steady-state or transient thermal analysis. The external surface areas of the SOLID70 elements that are exposed to fire, except the top surface of the slab, has been used to simulate the surface effects of convection and radiation that occur from the ambient air to the steel girder. LINK 33 is used to model the reinforcement. To account for the action between the concrete slab and the top flange of the steel girder, 3-D nonlinear surface-to-surface contact elements (CONTA174 and TARGE170). SURF152 is used for thermal load and surface effect applications. The whole model has been meshed with 50mm size after conducting mesh convergence study. For welding simulation bonded contact modelling has been used. Linear analysis is considered in contact modelling

C. Discretization for Structural Analysis

For structural analysis, the bridge girder was modelled with two elements, namely, element SHELL181 for the bottom flange, web, top flange, and stiffeners and element SOLID65 for the concrete slab. SHELL181 has four nodes with six degrees of freedom per node, three translations in x, y, and z-directions, and three rotations about the x, y and z-axes. This element can capture buckling of flange and web as well as lateral torsional buckling of the member and therefore is well suited for large-rotation, large-strain, and nonlinear problems. SOLID65 has eight nodes with three degrees of freedom, namely, three translations in the x, y, and z-directions. This element is used for 3D modelling of solids with or without reinforcement and is capable of accounting for cracking of concrete in tension, crushing of concrete in compression, creep, and large strains. The output from the thermal analysis (temperatures) was applied as a thermal-body load on the structural model to evaluate the mechanical response of a steel-concrete composite girder. To account for composite action between the concrete slab and the top flange of the steel girder, node-to-node interaction was discretized in the structural model as shown in Fig.1

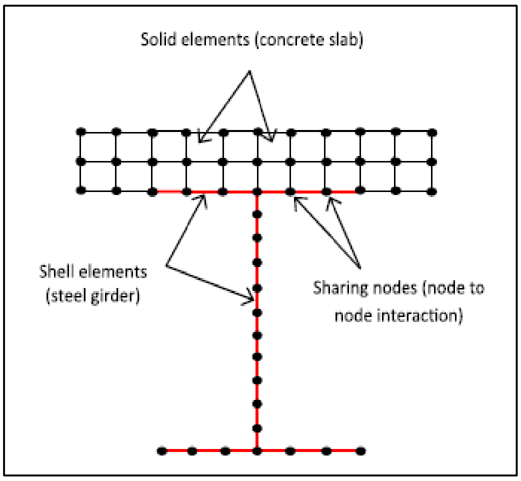

Fig 1.Composite action simulation

D. Material Properties

The thermal properties of constituent materials, namely, thermal conductivity, specific heat, and thermal expansion, which vary as a function of temperature were given as input to determine the thermal progression among steel beam and concrete slab. The mechanical properties of steel and concrete were also given as input. The thermal and mechanical properties of steel and concrete are assumed to follow the Eurocode 2 (CEN 2004) and Eurocode 3(CEN 2005) provisions.

E. Model Validaton

The validation process included comparison of thermal response predictions from the analysis with that reported in the fire test conducted by Aziz [1]. The steel beam was not insulated. The analysis was carried out with the mesh discretization and high temperature properties discussed earlier. The assembly was exposed to ASTM E119 fire exposure as in the fire test. Fig. 2 and Fig. 3 shows a comparison of predicted temperatures by the FEM model with those measured in the fire test. It can be seen that percentage error is about 2-3% when comparing the FEA and experimental results. This slight difference can be attributed to variation in the heat-transfer parameters, such as emissivity and convection coefficients.

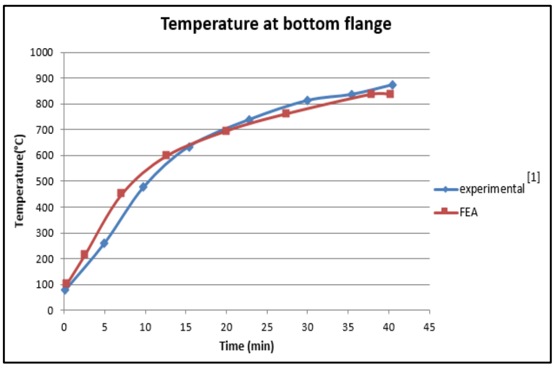

Fig 2. Comparison of temperatures in bottom flange as per FEA analysis with test data

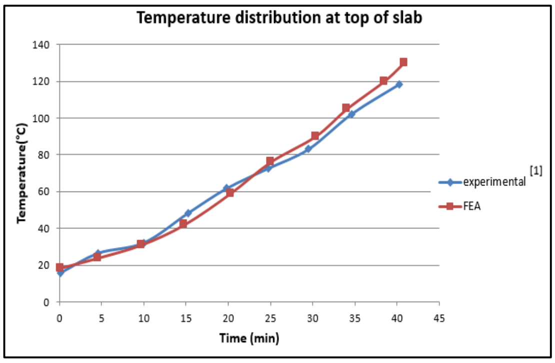

Fig 3. Comparison of temperatures in concrete slab as per FEA analysis with test data

IV. RESULTS AND DISCUSSIONS

A. Thermo-structural analysis

The fire-resistance analysis on the bridge girder has been carried out under an applied loading consisting of dead load plus live load.

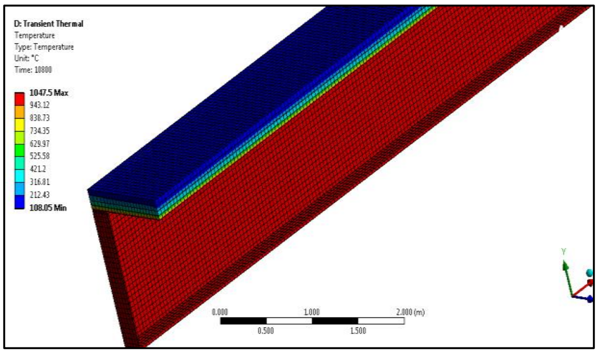

Fig 4.Thermal distribution along cross section

The self-weight of a girder section and that contributed by the tributary area of the concrete slab and wearing surface of the deck (13 kN/m) is considered in the dead load. For the live load, a uniformly distributed load (8 kN/m) representing Class AA tracked vehicle is considered. Symmetric criteria is considered for analysis.

Results from thermal analysis are plotted in Fig.4, which shows the temperature distribution of the steel-concrete composite girder as a function of time. It can be seen that due to high thermal conductivity of steel, maximum temperature occurs within steel.

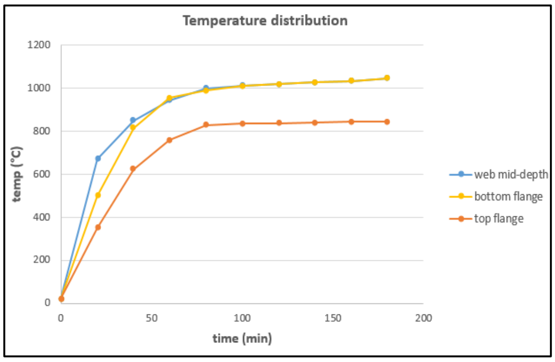

Fig 5. Temperature distribution along web and flanges

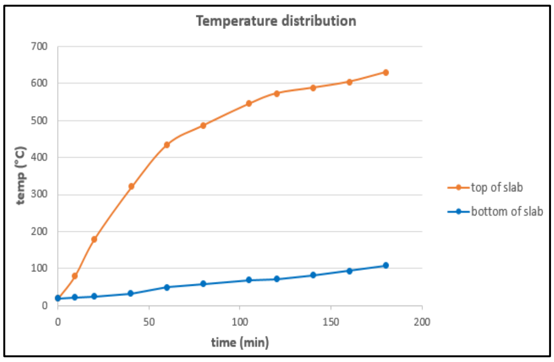

Fig 6. Temperature distribution along slab

It can be seen in Fig.6 that the top flange temperature is much lower than that of the bottom flange. "Heat sink" effect of the concrete slab which attracts much of the heat from top flange. Also, the temperatures in the web are slightly higher than those of the bottom flange, and this is because the web is much more slender (lower thickness) than the flanges, and this produces a rapid rise in web temperatures.

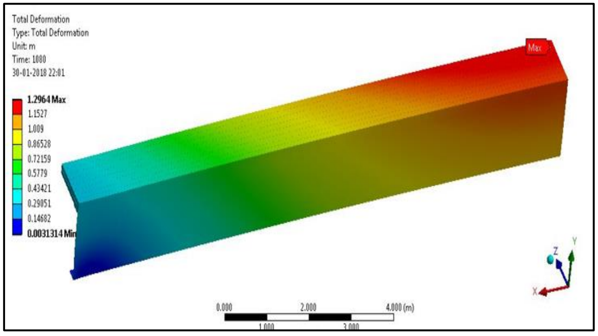

Fig 7.Total midspan deformation

Results from structural analysis is plotted in Fig.8. It can be seen that mid-span deflection gradually increases linearly with fire exposure time at the early stage. With temperature progression, the mid-span deflection starts to increase at a slightly higher pace. Degradation in strength and elastic modulus of steel resulting from increased temperatures in the steel girder. In the final stage the rate of deflection increases rapidly thus finally leading to spalling and collapse of the girder. This is because of the spread of plasticity in bottom flange and more buckling of the web.

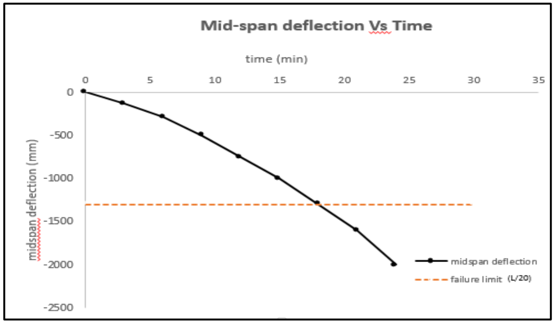

Fig 8. Effect of midspan deflection on thermo-structural loading

V. CONCLUSIONS

The following are the conclusions obtained from this study:

- Fire induces large curvature in beam, thus leading to “thermal bowing”.
- Thermal loads in structures result in thermal strains. Hence it is of utmost importance that the thermal loads must be considered in the design of girders.
- Composite action arising from steel-girder–concrete-slab interaction significantly enhances the fire resistance of bridge girders. Thus for the evaluation of the fire resistance of bridge girders composite action is to be properly accounted.

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