

## Numerical Analysis on Fire Resistance of Prestressed Concrete T-beam

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**ABSTRACT** : In predicting the likely behaviour of precast prestressed concrete T-beam in fire using advanced finite element methods, an improved numerical model using the 3-Dimensional non-linear finite element program ANSYS has been developed in order to investigate the thermal effects on the structures subjected to the ASTM E119 standard fire. A novel approach to the time-variant nonlinear finite-element analysis of concrete structures exposed to fire has been presented. The main novelty of the proposed formulation was to create an effective link between the simulation of thermal process and the finite element structural analysis. For this, the thermal properties of concrete have been assumed to be independent from the stress state, however; thermo-structural coupling achieved the proposed approach more general than the other procedures. This study set out to investigate the behaviour of simply supported prestressed concrete structural elements having restraint level subjected to standard ASTM E119 fires. In the analysis, high- temperature material properties and various restraint levels are discussed to determine failure. Results from the analysis indicate that fire scenario, concrete cover, depth of the section, position of strand, support condition and restraint levels have a significant influence on the fire resistance of PC T-beam.

**Keywords** – Fire Resistance, Prestressed Concrete T-beam, Thermo-structural Analysis, Nonlinear analysis, Restraint mechanism, ASTM E119, ANSYS.

### 1. INTRODUCTION

Structural fire safety is one of the primary considerations in building applications and hence, building codes generally specify fire resistance rating requirements for T-beams. PC T-beams are a common floor/roof assembly for such structures due to their desirable characteristics. Fire resistance ratings have, in the past, been assigned to various building components on the basis of results of standard fire tests. Such tests leave much to be desired. Furthermore, these fire provisions are valid only for a narrow range of parameters, and do not fully account for realistic fire, loading or restraint scenarios. In addition to being expensive and time consuming, fire tests often yield results that are misleading. Because of these shortcomings, a considerable research effort has been expended to develop data for the numerical analysis of structural members for fire resistance.

PC T-beams are analyzed using a finite element-based computer program ANSYS, under different fire, loading, and restraint scenarios. In the analysis of high-temperature material properties, various restraint levels, and material and geometric nonlinearities are accounted for, as well as realistic criteria applied to evaluate failure. Results from the parametric studies are used to study the thermal and structural response of double T-beams under realistic fire exposure, restraint, load intensity, and failure condition. In view of all the factors outlined above, this project set out to investigate the behaviour of simply supported prestressed concrete structural elements having restraint level subjected to standard ASTM E119 fires.

**Woods (1960)**[1] conducted one of the first fire tests on a PC beam at the Portland Cement Association (PCA) Fire Research Centre and concluded that concrete cover thickness for steel stands has a significant impact on fire resistance of PC beams. Behaviour of prestressed concrete structures in fire is complex, as thermal and load induced stresses are combined. **Selvaggio et al. (1964)** [2] concluded that load intensity has a significant effect on the fire resistance and restrained beams can perform better than unrestrained beams. **Franssen et al. (1997)** [3] formulated evolutionary algorithms to describe the heat transfer process induced by fire and to create an effective link between the simulation of the thermal process and the structural analysis. **Anderson et al. (1999)** [4] dictated the failure is mainly by strand temperature in simply supported T beam and by unexposed slab temperature in the continuous beam. **Zheng et al. (2007)** [5] derived formula for the stress in the unbonded prestressing steel wires in PC simply-supported slabs subjected to fire based on the experimental results. There by, the methods for calculating concrete thermal strain, transient strain and creep at elevated temperature were introduced, and total strain of a point in the concerned section and total curvature caused by load and

temperature can be calculated considering time-dependent effect. *Bailey (2008)*[6] modelled a bonded post-tensioned one way spanning concrete slab under fire and validated with the test results. *Xin et al. (2011)* [7] prepared finite element analysis; thermodynamic properties of nine unbonded prestressed concrete beams are numerical simulated under high temperature in this paper. *Biondini et al. (2011)* [8] presented a novel approach to nonlinear finite-element analysis of concrete structures exposed to fire. The main novelty of this formulation is the use of a special class of evolutionary algorithms to describe the heat transfer process induced by fire and to create an effective link between the simulation of the thermal process and the structural analysis. *Kasat et al. (2012)* [9] studied the two dimensional finite element analysis of prestressed concrete beams by using ANSYS to understand the response of prestressed concrete beams due to transverse loading and *Shov et al. (2012)* [10] developed a computer model of reinforced concrete slab in ANSYS Workbench and ANSYS Mechanical to assess their fire rates.

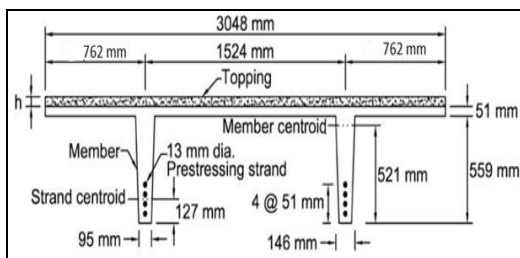
## 2. NUMERICAL STUDIES

Numerical analysis is carried out to study the effect of various factors governing the fire resistance of PC T-beams. The proposed methodology has to be validated through applications simply supported beams tested in laboratory, a precast beam with different slab thickness and elastic restraints under standard fire and other structural loads is analysed through finite element analysis. Fire resistance evaluation is done by thermal analysis. It is emphasized that the possibility of accounting for a thermo mechanical coupling makes the proposed approach more general than other procedures in which the finite element analysis is based on temperature contours obtained from a separate thermal fire analysis.

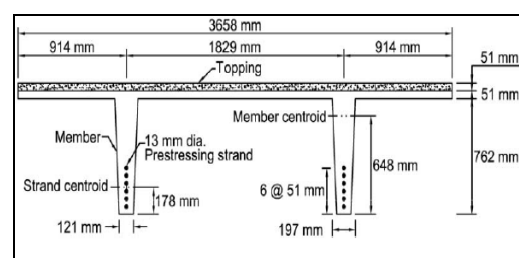
Numerical studies of PC T-beams are carried out by using a special-purpose finite-element computer program ANSYS, which is capable of predicting the fire response of structural systems. In this computer program, the fire resistance of a structural system is analyzed through a two-fold thermo-structural analysis as in *Sallomi et al. (2008)* [11]

### 2.1 Geometry of the model

The cross-sectional details of the PC double T-beam provided in *Kodur et al. (2011)* [12] tested under ASTM E119 fire exposure for the thermal analysis is shown in fig 1. The beams are analysed with various slab thickness of 51, 76, 102, 121 and 152mm. The cross-sectional details of two models named 12DT 32 with and without stiffness is given below for the analysis for investigating the structural response of the model under fire with structural loads.



**Fig1** Geometry of model for thermal analysis



**Fig 2** 12DT 32 models for thermo-structural analysis

### 2.2 Finite elements

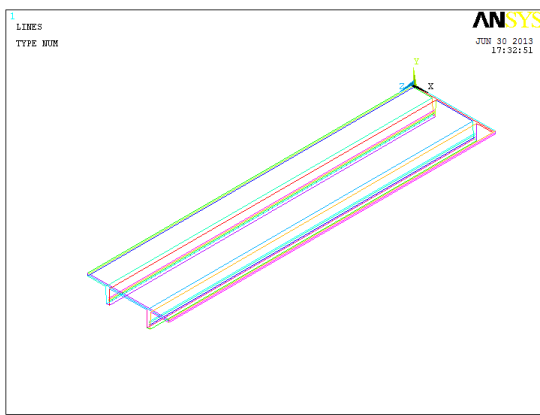
For thermal analysis, concrete is modelled with the element ‘solid 70’ which has a three-dimensional thermal conduction capability and eight nodes with a single degree of freedom (temperature) at each node, also it can compensate for mass transport heat flow from a constant velocity field and while analysed structurally the element is replaced by ‘SOLID 65’ which has eight nodes with three degrees of freedom at each node and translations in the nodal x, y, and z directions. The element is capable of plastic deformation, cracking in three orthogonal directions, and crushing as discussed in *Job Thomas (2002)* [13].

‘LINK33’ is used to model the strand, which is a uniaxial element with the ability to conduct heat between its nodes and in structural analysis it is replaced by ‘LINK 8’ which has a single degree of freedom, temperature, at

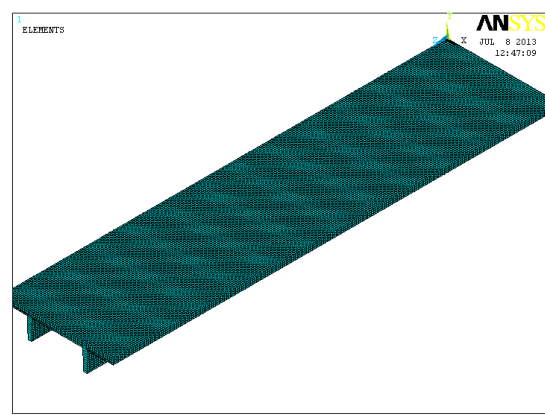
each node point. Strands are modelled using 3-D spar elements (Link 8) and these elements allow the elastic-plastic response of the strands. COMBIN14 is used for the axial restraint in thermal as well as structural modelling and it has longitudinal or torsional capability in one, two, or three dimensional applications. The longitudinal spring-damper with no mass option is a uniaxial tension-compression element with up to three degrees of freedom at each node: translations and rotations in the nodal x, y, and z directions. No bending or torsion is considered. No bending or axial loads are considered. The spring-damper element has no mass.

### 2.3 Modelling of PC T-beam

The 3-D modelling of PC T-beam is carried out by generating the key points in active coordinate system. The cross section of the beam is created by joining the line elements with the obtained key points. To obtain the volume by extrude the area created by the previous line elements. The strands are inserted as line elements shown in fig 3.

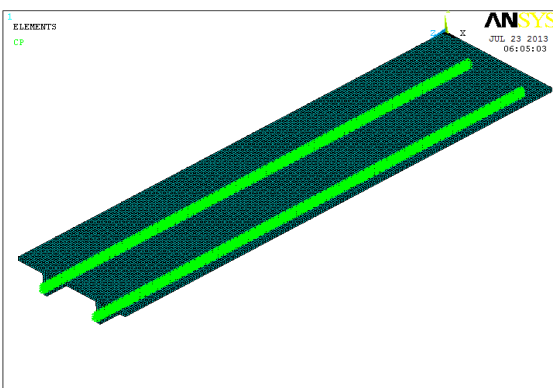


**Fig 3.** Line sketch of the model from ANSYS

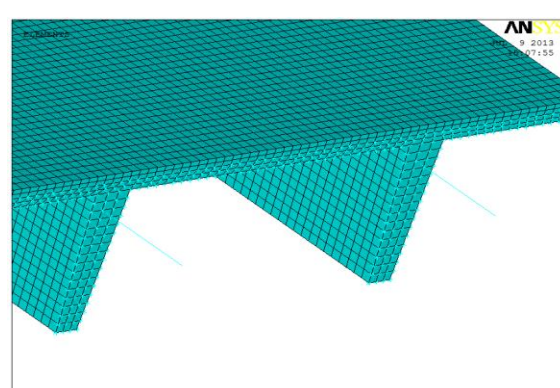


**Fig 4.** Meshed view of the model in ANSYS

Thermal conductivity, specific heat and density of concrete of compressive strength 40MPa and prestressing steel of a 13mm diameter 1860MPa grade low-relaxation cold drawn steel are taken from the Eurocode. Each fiber is assigned a nonlinear temperature-dependent material property (Poisson's ratio, compressive strength, Young's modulus and Yield strength) in accordance with Eurocode 2 [14] and as included in *Buchanan (2002)* [15] is constant along the length of the beam element. Model is then meshed like in fig 4 and the bonding between concrete and reinforcement is obtained by coupling shown in fig 5. As mentioned in *Wolanski (2004)* [16] to bring prestressing effect initial strain is entered induced by strand is assumed to be stressed to 1172 MPa to account for the initial jacking force ( $0.75 f_{pu}$  where  $f_{pu}$  is the ultimate tensile strength of strand) and minimum stress loss 207MPa as per *PCI Design Handbook (2004)* [17] on account of all losses.



**Fig 5.** Coupling of nodes of concrete and strands



**Fig 6.** Position of stiffness on PC T-beam

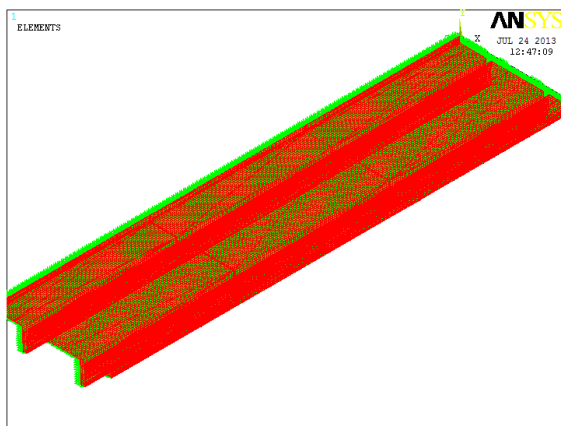
The ‘COMBIN14’ having very small dimension connecting the nodes of ‘SOLID65’ elements on the position of the eccentricity between thermal induced force and the centre of gravity of the each T-section has been used to model the stiffness in the present analysis. To provide the spring mechanism the contact element for the nodes on the axial spring to the area of the concrete T-section is created by using the ‘contact manager’ in the ANSYS is shown in fig 6. For simulating restraint effects, a spring element is incorporated and various degrees of restraint are simulated by modifying the cross-sectional area of the member.

**2.4 Loading and boundary condition**

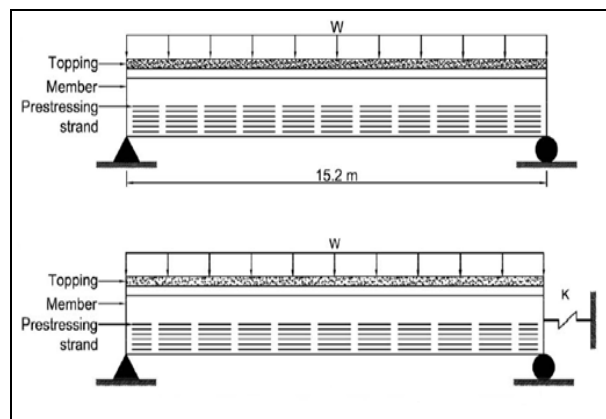
The finite element model for this analysis is carried out for transient and standard fire load ASTM E119 [18] is applied at the bottom and side portion shown in fig 7 by creating a new table given below in ANSYS. A sequentially coupled physics analysis is the combination of analyses from different engineering disciplines which interact to solve a global engineering problem. For convenience, the solutions and procedures associated with a particular engineering discipline will be referred to as a physics analysis. When the input of one physics analysis depends on the results from another analysis, the analyses are coupled.

**TABLE 1** ASTM E119 fire load in ANSYS

Time (seconds)	ASTM E119 temperature (°C)
0	20
300	538
600	704
1800	843
3600	927
7200	1010
14400	1093
28800	1260



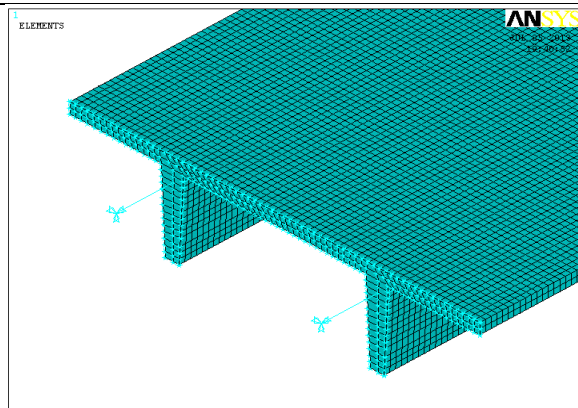
**Fig 7** Model subjected to ASTM E119 fire load



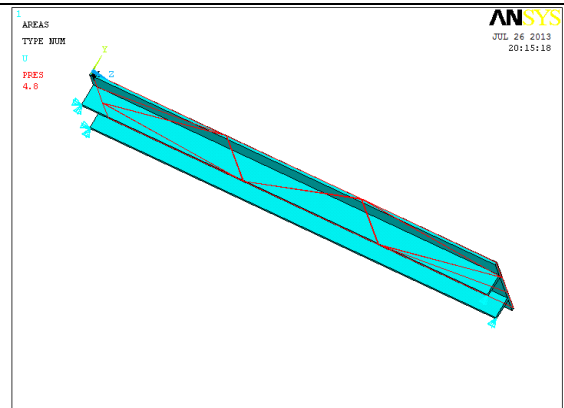
**Fig 8** Support condition and stiffness mechanism

The model is allowed for the simply supported condition as in fig 8, one end portion is vertically restrained to represent the roller connection and the other end is restrained in Y and Z direction to provide a pinned mechanism. But in the case of stiffness model one end of the stiffness has to be fixed by restrained the all degree of freedom as shown in fig 9 and the boundary condition applied to the model in ANSYS.

A structural load of 4.8 kN/m<sup>2</sup> is applied as a pressure at the top surface of the slab along with the temperature from ANSYS in fig 10. The saved ‘.rth’ file has to be coupled with the structural effect so that this couple the results from the solution of thermal environment to the information prescribed in the structural environment and uses it during the analysis. Before the analysis set the reference temperature as 20°C and the system is solved.



**Fig 9** Boundary condition of Stiffness



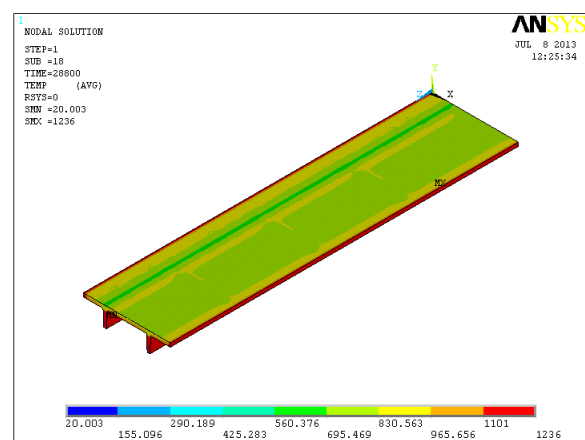
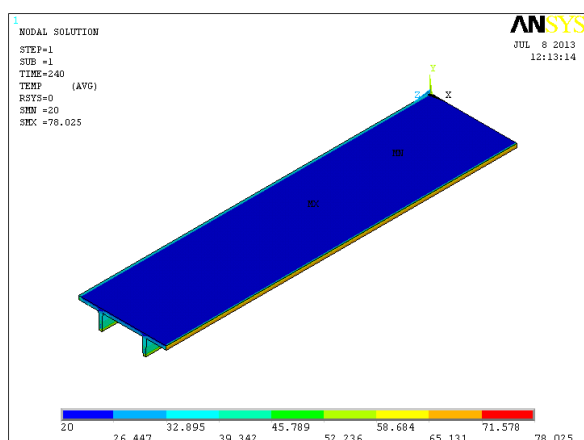
**Fig 10** Model subjected to a uniformly distributed load

### 3. VALIDATION

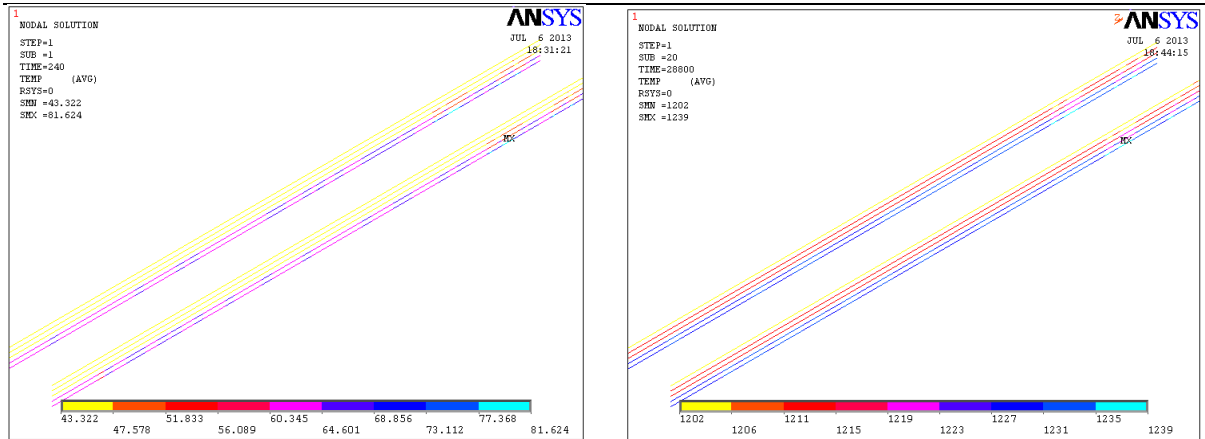
The numerical model is validated by comparing predictions from the model with measured data from fire test on PC T- beams. Due to the lack of comprehensive test data for any one beam, test data from the first beam are utilized to compare the predicted unexposed slab temperatures, and to compare strand temperature. PC T- beam 12DT 32 with and without stiffness is validated for the thermo- structural analysis and mid- span deflection is compared with the test results.

#### 3.1 Thermal Analysis: - Temperature- time curve

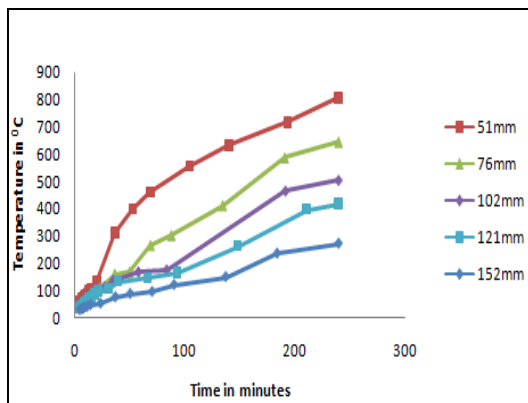
Results from the fire tests were used to generate fire ratings 30, 60, 90, 120 and 180 minutes by increasing the slab thickness from 51, 76, 102, 121 and 152mm. Typical unexposed slab thermal contours and strand temperature at initial and end step is shown in fig 11 and fig 12 respectively. In fig 13 and 14, graph obtained as a function of time according to nodal temperature at different time step for the different slab thickness from the analysis. In all cases, the temperatures in the unexposed side of the beam initially rise slowly in a linear fashion after that the temperature increase at a higher rate and follow a similar trend as that of the ASTM E119 fire curve. In all strands, the temperature gradually increases, with temperatures in strand 1 rising more rapidly than strand 5. From this it is very clear that the strand temperature plays a significant role in the failure of prestressed concrete beams under fire condition. The beam and strand temperature results follow similar trends as the actual fire scenarios. Fig 18 gives the predicted fire resistance values for various slab thickness which are almost near to the test ratings over the entire range with data points lying within 15%.



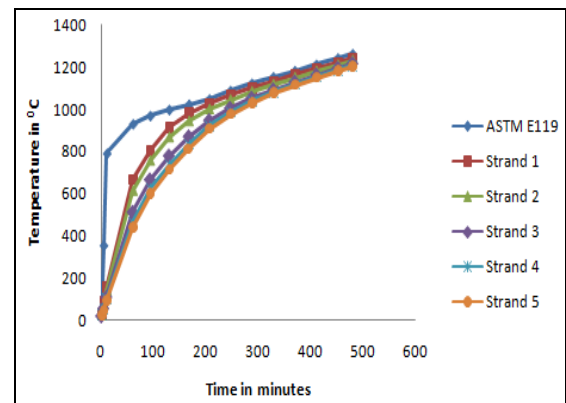
**Fig 11** Thermal contour of model at initial and final time step



**Fig 12** Thermal distribution of strands at initial and final time step respectively



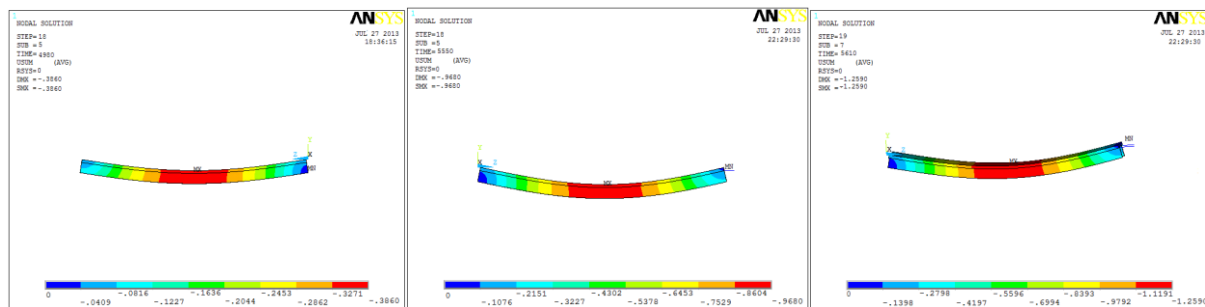
**Fig 13** Unexposed surface temperature – time graph



**Fig 14** Strand temperature – time graph

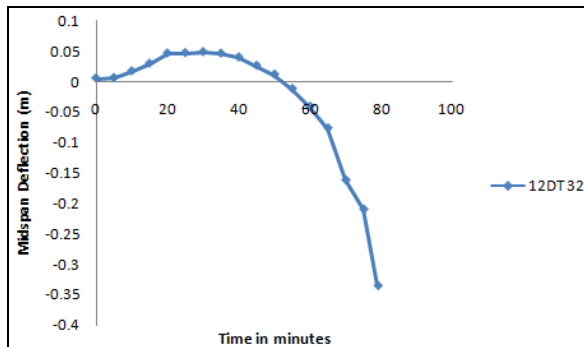
**3.2 Thermo- structural analysis: - Mid span Deflection- time graph**

The T- beams are modelled with different axial spring stiffness. The axial restraint stiffness (k) of the beam ranged from 0 to 100%. The restraint mechanism is intended to act as a spring with a stiffness of  $\left(\frac{E_s A_s}{l}\right)$ . Variable stiffness is applied through altering the cross-sectional area of the spring element, since the elastic modulus and the length are constant.

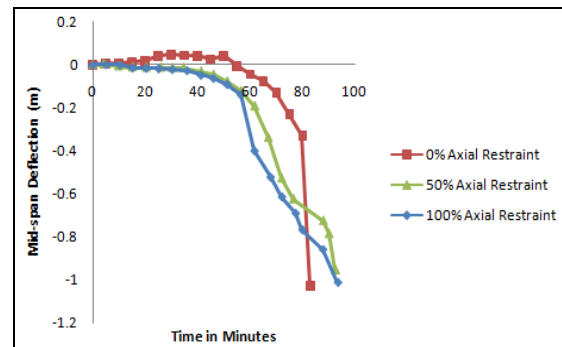


**Fig 15** Deflection diagram of 12 DT 32 with 0%,50% and 100% axial restraint from ANSYS.

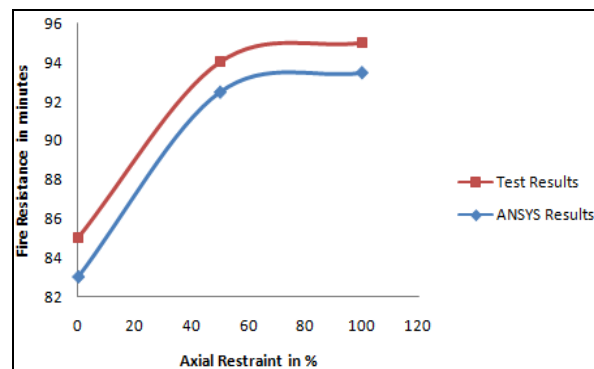
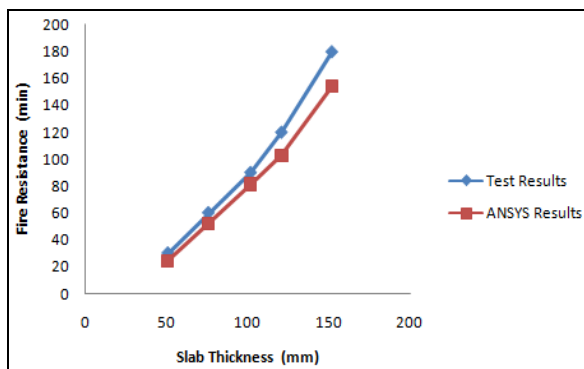
The effect of axial restraint on the fire performance of PC T- beams is evaluated through applying 0%, 50% and 100% axial restraint and structural response is given below. It is noticed that graph in fig 16, deflection of the axial restrained beam shifts gradually from positive to negative once the prestressing strands begin to lose significant stiffness. However, when the unrestrained beam starts to lose significant stiffness, there is no external effect to delay its failure. Thus, axial restraint can improve the fire resistance of PC beams.



**Fig 16** Mid-span deflection time graph of model



**Fig 17** Mid-span deflection time graph with axial restraint



**Fig 18** Comparison of Test and ANSYS results for the slab thickness and restraint effect.

#### 4. CONCLUSIONS

Finite Element Analysis is conducted to develop numerical models for assessing the fire performance of precast prestressed concrete systems in concrete framing structures. The present work has been primarily concerned with the numerical modelling of the structural behaviour of prestressed concrete beams with variable parameters, such as concrete toppings, concrete cover, strand temperature and restraint level of the system under the fire. Based on the finite element analysis conducted in ANSYS on the Prestressed Concrete T-beams, the following conclusions are arrived.

- An investigation into the fire performance of Prestressed Concrete T-beam is performed and it is found that the fire resistance is dependent on the cover to the reinforcement, topping slab thickness and restraint level.
- Practical techniques can be adopted for the achievement of required fire resistance of the Prestressed concrete beams.
- A detailed thermo-structural non-linear finite element ANSYS model for the three dimensional analysis of prestressed concrete T-beam at elevated temperature has been developed and presented.
- The thermal analysis is conducted for the different slab thickness and the variation of the thermal profiles of the slab and the tendons are also plotted.

- The thermal contours reveal that a thicker topping slab delays the temperature rise in the unexposed surface compared to the thinner topping slab and an increase of 49% in thickness of topping slab improves fire resistance by 113%.
- The percentage difference of fire resistance of experiment and the ANSYS model varies between 10 and 15%.
- Fire resistance of Prestressed Concrete T-beam is often governed by limiting strand temperatures for slender stem where adequate cover thickness is provided. The Eurocode provisions results in 90 minutes fire rating for the given cover thickness of the particular PC beam 12DT 32.
- Developed stiffness connection to explain the restraint mechanism is useful in predicting the structural behavior of simply supported prestressed concrete T-beam.
- For web supported PC T-beam, the effect of only high axial restraint stiffness against the beam is significant to varying the fire resistance.
- The fire resistance of the simply supported PC T-beam is found to be increased by 12.56% then 100% stiffness is provided at the centroidal axis.
- Axial restraint can improve fire resistance of Prestressed Concrete T-beam, but the levels of restraint depends on the type of restraint, support condition like flange support and web support and variable stiffness offered by adjoining members.
- The numerical model has been validated against physical laboratory testing data and showed good agreement with the actual structural behaviour.

## 5. ACKNOWLEDGEMENT

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## REFERENCES

- [1] Woods H , Fire resistance of prestressed concrete, *Journal of Structural Engineering*, 1960, Vol. 86: 53–56, No. 11.
- [2] Selvaggio SL and Carlson CC, Fire resistance of prestressed concrete beams study: influence of aggregate and load intensity, *PCI Journal*, 1964, Vol. 6: 10–25, No. 4.
- [3] Franssen JM and Bruls A, Design and tests of prestressed concrete beams. In: Proceedings of 5th International Symposium on Fire Safety Science *London, International Association for Fire Safety Science*, 1997, pp. 1081–1092.
- [4] Anderson N E and Lauridsen D H, TT-roof slabs, Technical Report. *Danish Institute of Fire Technology*, 1999.
- [5] Wenzhong Zheng and Xiomeng Hou, Experiment and Analysis of PC Simply-supported slab subjected Fire, *School of Civil Engineering, Harbin Institute of Technology, Harbin, P R China*, 2007.
- [6] Bailly C G and Ellobody E M A, Modelling of Bonded Post-tensioned Concrete Slabs in Fire, *Structures and Buildings*, Tanta University, Egypt, 2008.
- [7] Haung Xin and Y E Xian – guo, Numerical Analysis of Thermodynamic Properties of Prestressed Concrete Beam under high temperature, *School of Civil Engineering, Hefei University of Technology, China*, 2011.
- [8] Fabic Biodini and Andrea Nero, Cellular Finite Element for Nonlinear Analysis of Concrete Structures under Fire, *Journal of Structural Engineering, ASCE*, 2011.
- [9] Abhinav. S. Kasat and Valsson Varghese, Finite Element Analysis of Prestressed Concrete Beams, *International Journal of Advanced Technology in Civil Engineering*, ISSN-2231-5721, 2012, Volume-1.
- [10] Vadim Kudya Shov, Nguyen Thanh kien and Aleksandr Lipandin, Fire Resistance Evaluation of Reinforced Concrete Structures, *Institute of Command Engineers of the Ministry of Emergencies of Belarus, Byelorussian State Technology University*, 2012.
- [11] Kareem N Sallomi, Response of Composite Concrete I-beams under the Effect of Fire and External Loadings, *The Iraqi Journal for Mechanical and Material Engineering*, 2008.
- [12] Kodur V R, A Performance-based Approach for Evaluating Fire Resistance of Prestressed Concrete Double T-beams, *Journal of Fire Protection Engineering*, 2011.
- [13] Job Thomas , Nonlinear Analysis of Shear Dominant Prestressed Concrete Beams using ANSYS, *Indian Institute of Science, Bangalore, India*, 2002.
- [14] Eurocode 2 (EC2), *Design of concrete structures. ENV 1992-1-2: General Rules –Structural Fire Design*. Brussels, Belgium: European Committee for Standardization, 2004.
- [15] Buchanan A H, *Structural Design for Fire Safety*, John Wiley & Sons, New York, USA, 2002.
- [16] Antony J Wolanski B S, Flexural Behaviour of Reinforced and prestressed Concrete Beams using Finite Element Analysis, *Faculty of the Graduate School, Marquette University, Milwaukee, Wisconsin*, 2004.
- [17] ASTM E119-08, *Standard methods of fire test of building construction and material*, Conshohoken, PA: American Society for Testing and Materials International, 2008.
- [18] PCI Design Handbook: Precast and prestressed concrete, *Precast Prestressed Institute, Chicago*, 2004.