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Finite Element Modeling for Effect of Fire on Steel Frame

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ABSTRACT
This research is intended to be preliminary study lending to the detailed behavior of steel member i.e. Plane Frame. This paper shows the behavior of steel structures in fire the use of steel in building construction and its behavior when exposed to fire is presented. Fire performance of structural steel at elevated temperature includes the study of steel frame subjected to fire. Also the effect of stress strain temperature on the fire performance of structural steel should be observed. The behavior of a steel frame in a fire depends on many factors including the properties of the steel and the coating material on it. Computer application based on ANSYS software used to study the various parameters affecting the overall behavior of steel structures in fire is presented. The present paper shows the effects of stress–strain relationships on the fire performance of steel frame exposed to uniformly increasing temperature when steel is unprotected and protected with concrete using FEM.
Key words: Steel frame, Elevated temperature, Fire performance, Stress-Strain, Finite Element Model (FEM).

I. INTRODUCTION

Structural steel has been widely used throughout the world. It is one of a designer's best options in view of its advantages over other materials [1]. Steel is available in a range of discrete size, and its ductile behavior allows plastic deformation upon yielding, therefore avoiding brittle failures. In reinforced concrete structures, steel enhances the concrete strength by carrying the tensile forces [2]. It is also commonly used to reinforce timber constructions. In spite of its advantages, steel on its own is vulnerable in fire [3]. Elevated temperatures in the steel cause reduction in its strength and stiffness which eventually leads to failure due to excessive deformations [4]. This is crucial in steel in compared with concrete or timber members as steel conducts heat very well and often comes in thin or slender elements [5]. In structural design, there are a few functional requirements such as those stated in Clause C4 of the New Zealand Approved Document (BIA, 1992):

"Buildings shall be constructed to maintain structural stability during fire to:

a. Allow people adequate time to evacuate safely,
b. Allow fire service personnel adequate time to undertake rescue and fire fighting operations,
c. Avoid collapse and consequential damage to adjacent household units or other property."

There are a lot of different methods for protecting structural steel to maintain its strength and stability in fire, but little is known about the True behavior of the steel members under various support conditions and heating patterns [6].

The recommended fire resistance to be applied to the steel structures is usually determined based on furnace tests on single elements such as a beam or a column [7]. Contrary to popular belief, an unprotected steel element that is a part of a large complex structure may have a sufficiently high level of fire resistance to perform well in fire. This is due to the ability of the overall structure to redistribute loads from the heated area to the cooler Neighboring elements [8].

The lack of understanding of the true behavior of steel elements in fire leads to inefficient and uneconomical design [9]. To assess the overall performance of steel frames, it is important to understand the detailed behavior of a single beam with several support conditions that represent various elements in a complex structure [10].

II. MATERIAL USED AND THEIR PROPERTIES

2.1. Steel

The physical properties of steel are totally different from it component element viz. iron and carbon one of the major property of steel is the ability to cool down rapidly from an extremely hot temperature after being subjected to water or oil physical properties depends on percentage composition of the constituent element and the manufacturing process a particular amount of carbon can be dissolved in iron at specific temperature.

The physical properties of steel include high strength, low weight durability, flexibility and corrosive resistance. Steel as well all knows, offer great strength though it is light in weight in fact the ratio of strength to weight for steel is the lowest than any other building material as of now .by the term flexibility it means steel can easily molded to form any desired shape .

Unlike the constituent element iron steel does not corrode easily on being exposed to moisture and water the dimensional stability of steel is desired property as the dimension of the steel remains unchanged even after many years or being subjected to extreme environmental condition steel is a good conductor of electricity i.e. electricity can pass through steel.

Steel grade are classified by many standard organization based on the composition and physical properties of the metal the deciding factor of the grade of steel is basically the hardness of the metal which differ s depending on the percentage of carbon content. higher the carbon content the harder and stronger the steel metal along with more chances of fracture high quality steel contain less carbon yet retains the strength and hardness.

Earlier forms of steel consisted of more carbon, as compared to the present day steel. Today the steel manufacturing process is such that less carbon is added and the metal is cooled down immediately, so as to retain the desirable physical properties of steel. there are other types of steel such as galvanized steel and stainless steel (corrosion-resistance steels) .Galvanized steel is coated with zinc to protect it from corrosion whereas stainless steel contain about 10 percent of chromium in its composition Structural steel has been used throughout the world it is one of a designers best options in view of its advantages over other materials. Steel is available in arrange of discrete size, and its ductile behaviour allows upon yielding. Therefore avoiding brittle failures. In reinforced concrete structures, steel enhances the concrete strength by carrying the tensile forces .It is also commonly used reinforce construction.

In spite of its advantages, steel on its own vulnerable in fire . Elevated temperature in the steel , cause reduction in its strength and stiffness , which eventually leads to failure due to excessive deformations. This is crucial in steel compared with concrete or timber member as steel conducts heat very well and often comes in thin or slender elements.

2.2. Thermal properties of steel

2.2.1 Thermal elongation

The thermal elongation of steel is the increase in length of a member caused by heating divided by the initial length. Figure 2.1 shows the relationship of Elongation and the temperature of steel according to the Euro-code 3 (EC3, 1995). The Discontinuity in the thermal elongation between 750^{o}c and 860^{o}c is due to a phase Transformation in the steel. The following equations from the Euro-code 3 (EC3, 1995) Describe the thermal elongation relationships in steel. The thermal elongation of steel is determined by the Euro-code 3 formulae as a function of the steel temperature and illustrated in Figure 2.1.

For $20^0C<T<750^0C$

E thermal$=1.2x10^{-5}xT+0.4x10^{-8}xT^2-2.416x10^{-4}$

For $750^0c<T<860^0C$

E thermal$=1.1x10^{-2}$

For $860^0C<T<1200^0C$

E thermal$=2x10^{-5}xT-6.2x10^{-3}$

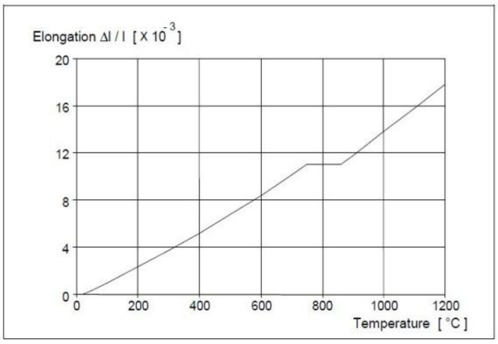


Fig.2.1 Thermal elongation of steel as a function of temperature (EC3, 1995)

In simple calculation models, assuming the thermal elongation to have constant relationship with the temperature of the steel, the elongation can be taken as:

Thermal Strain$=14*10^{-6}(T_S-20)$

2.2.2 Thermal conductivity

Thermal conductivity is the ability of a material to conduct heat and is defined as the ratio of heat flux to the temperature gradient. For steel materials, it is dependent on steel composition as well as the steel temperature. Figure2.2 shows that the EC3 steel model has a linear reduction in thermal conductivity from 20 to 800 C and is constant. The variation of the thermal conductivity of steel can also be determined from the following Euro code formulae and is illustrated below:

For $20^0C<T_S<800^0C$

Thermal conductivity$=54-3.33x10^{-2}T_S$

For $800^0C<T_S<1200^0C$

Thermal conductivity=27.3

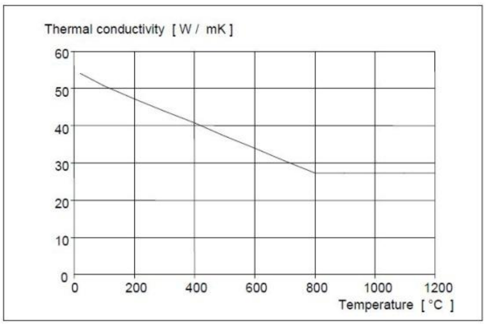


Fig.2.2 Thermal conductivity of steel as a function of temperature (EC3, 1995)

Thermal conductivity of steel with temperature greater than 1200 ^{0}C is not defined in the Euro code 3 as most structural steel members can hardly survive such heat. The value of 27.3 W/m K is taken for T > 1200 ^{0}C if such case needs to be considered as dealt with in the thermal analysis. For simple calculation models that are independent of the temperature, the value of 45 W/Mk can be adopted.

2.2.3. Specific heat

Specific heat is the ability of a material to absorb heat. The specific heat of steel is independent of steel composition and varies only with the temperature. Figure 2.3 shows the relationship of specific heat and temperature of steel according to the Euro code 3 (EC3, 1995). At 730 ^{o}c there is a metallurgical change in the steel crystal structure that causes a peak specific heat. The equations from the Euro-code 3 (EC3, 1995) for the specific heat relationships are shown below.

For $20^0C<T_S<600^0C$

$Cs=425+7.73x10^{-2}\ Ts-1.69x10^{-3}\ T^{\ 2}+2.22x10^{-6}\ T^3$

For $600^0C<T_S<735^0C$

Cs=666+13002/(738-Ts)

For $735^0C<T_S<900^0C$

Cs=545+17820/(Ts-731)

For $900^0C<T_S<1200^0C$

Cs=650

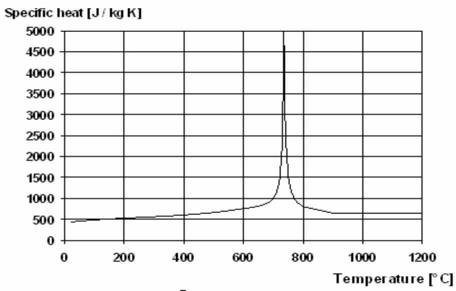


Fig.2.3 Specific heat of steel as a function of temperature (EC3, 1995)

Simple calculation models take the specific heat of steel as 600 J/kg K, independent of the temperature of the steel. For temperature greater than 1200 ^{0}C, the specific heat is taken as 650 J/kg K.

2.3 Mechanical properties of steel

2.3.1 Components of strain

Strain is the measure of elongation of an element with respect to its original length. The change in strain with temperature is defined as:

Change in strain (dl/l) $=E_{th}\,(T)+E_6\,(6,T)+\ E_{Cr}\,(6,T,t)$

Where,

E_{th} is the thermal strain;

E_6 is the stress-related strain;

E_{Cr} is the creep strain.

The thermal strain is the elongation of the material due to heat, and is commonly referred to as thermal expansion as described by Rotter (1999) and is summarized in section . It is a very important aspect especially in larger structures with the elements restrained by the adjacent members.

2.3.2 Creep strain of steel tested in tension

Creep strain in structural steel only becomes significant at temperatures over 400°C or 500°C. Kirby and Preston (1988) have shown that the creep is highly dependent on Temperature and stress level of the steel (Figure 2.4). The creep strains increase rapidly where the curve becomes nearly vertical at higher temperatures. Therefore, creep deformations are important when the steel members approach their collapse loads. The Euro code 3 (EC3, 1995) describes that the stress-strain relationships usedFor design implicitly include the likely deformations due to creep during the fire exposure.

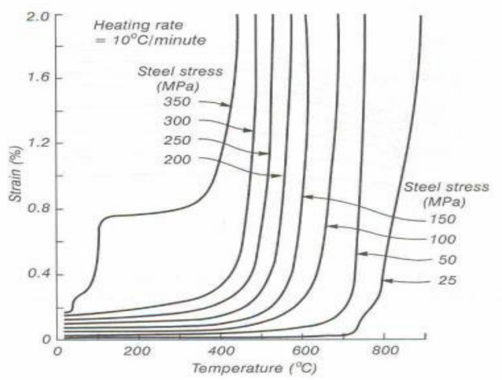


Fig.2.4 Temperature and stress level of the steel

2.3.3Stress-strain relationship

Harmathy (1993) has obtained typical stress-strain relationships for structural steel at elevated temperatures (Figure 2.5). The figure shows that yield strength and modulus of elasticity both decrease with increasing temperature. However, the ultimate tensile strength increases slightly in the temperature range of 180 ^{0}C to 370 ^{0}C before decreasing at higher temperatures. Figure 2.5 shows the stress-strain relationships of hot-rolled structural steels at elevated temperatures given in the Euro code 3 (EC3, 1995) for designing steel members subjected to elevated temperatures.

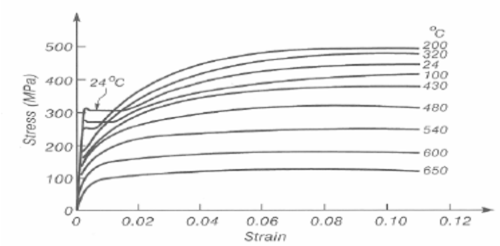


Fig.2.5 stress-strain relationships for structural steel at elevated temperatures

2.4 Concrete

Concrete a homogeneous mixture made up of cement, sand and aggregate. All the constituent of concrete are bad conductor of heat and electricity. Also it is basically used for R.C.C. structure .but we can use the concrete as a thermal insulating material with a suitable thickness is provided on a steel frame so that the effect of fire should be reduced.

III. METHODOLOGY

Analyses of steel frame with specify reference to thermal load arising from the fire disaster.

3.1 INTRODUCTION

For the design of plane building frame in steel, the problem of the analysis with respect to thermal loads arising from the fire has nowadays acquired significant importance, large of such activates as accidents, sabotage etc. The structural behavior of the frame in such cases in governed by phenomenon of material non linearity coupled with geometric non linearity. The problem of analysis is thus quite complex. In the present work simplistic approach of analysis through stepwise linear analysis is taken up Hence in this the method of linear analysis is presented in the next chapter the methodology presented here is applied to carry out stepwise analysis simulating the nonlinear behavior mentioned above.

3.2 METHODOLOGY

The linear plane frame analysis is carried out Following steps

Step 1 Finite element idealization of the frame structure

Step 2 Formation and solution of the equations governing equilibrium of the idealized frame subject to approach boundary conditions

Step 3Evaluation of the structure response of the elements of the idealized frame

This methodology is discussed through illustrative frame with details shown in figure3.1

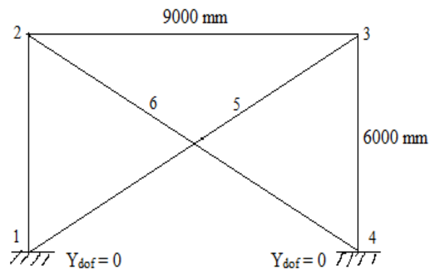


Fig: 3.1 Schematic of truss

Step 4.After that calculating the thermal strain analytically using the formula given in Euro-code 3.

Step 5.Using FEA Formulation of truss model shown in fig. 3.2

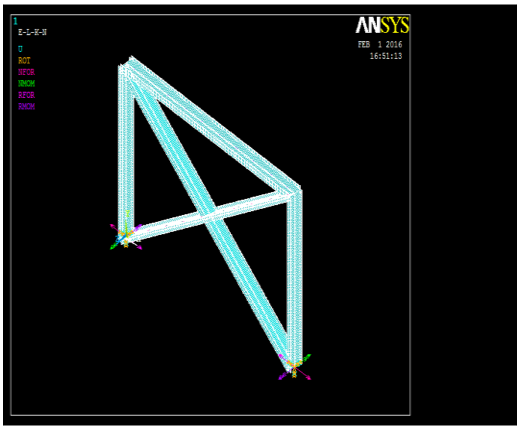


Fig: 3.2 Truss model using FEA

Step 6.Finding the thermal strain and deformation

Step 7.After that validate the analytical result and result using FEA.

IV. ANALYTICAL INVESTIGATION

The thermal elongation of steel is determined by the Euro-code 3 formulae as a function of the steel temperature.

For $20^0C<T<750^0C$

$$E\ thermal=1.2x10^{-5}xT+0.4x10^{-8}xT^2-2.416x10^{-4}$$

For $750^0c<T<860^0C$

$$E\ thermal=1.1x10^{-2}$$

For $860^0C<T<1200^0C$

$$E\ thermal=2x10^{-5}xT-6.2x10^{-3}$$

The analytical investigation include the study of behavior of steel frame subjected to fire .the study include parameter like thermal stress, thermal strain and temperature.

The temperature and corresponding thermal strain is as shown in Table: 4.1 below.

Sr.No.	Temperature	Thermal strain
1	100	0.9984×10^{-3}
2	110	1.1268×10^{-3}
3	120	1.1256×10^{-3}
4	130	1.386×10^{-3}
5	140	1.5168×10^{-3}
6	150	1.6484×10^{-3}

V. FINITE ELEMENT ANALYSIS OF SPECIMEN

5.1. Introduction:

This chapter consists of modeling and analysis of truss members. Truss members are made up of steel material having I section and I section is surrounded with concrete. Effect of temperature and self-weight of both types of specimen on elastic strain is obtained by using FEA package ANSYS 14.

5.2 Finite Element Modeling and Analysis:

Two dimensional finite element analysis has been carried out in ANSYS 14.5. Schematic of truss is as shown below in Fig.5.1

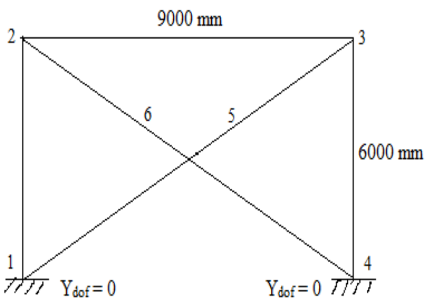
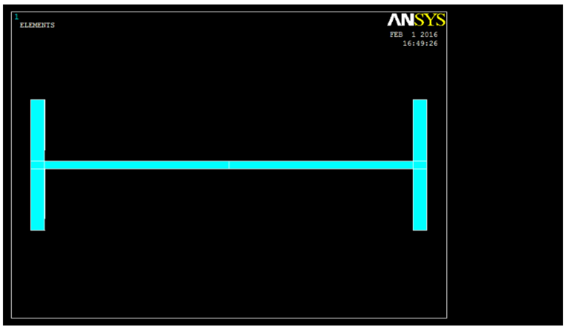
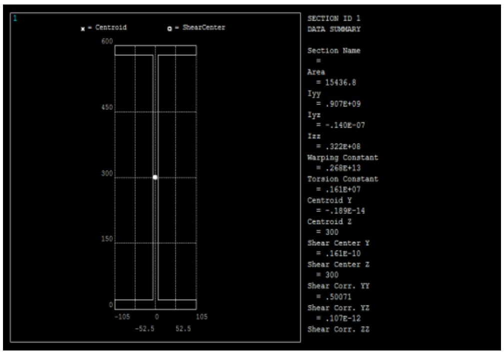


Fig. 5.1 Schematic of truss

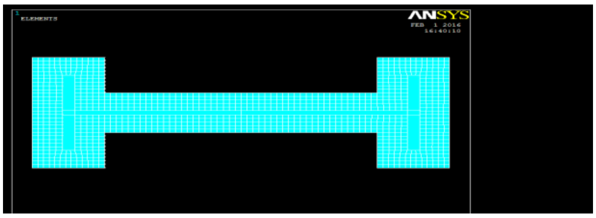
In first step of modeling, effect of temperature is determined for truss members having I section which is made up of steel material. In second step of modeling I section of steel material is layered by concrete. CAD model of both sections is as shown in figure.



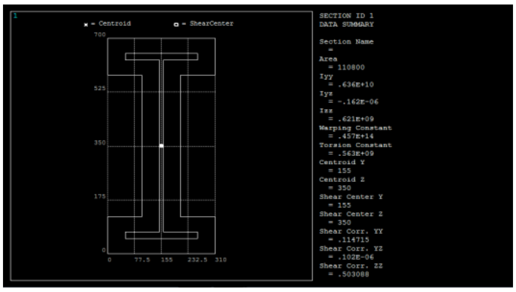
5.2. (A) I section with steel material only.



5.2. (B) I section with geometric details.



5.2. (C) Composite I section.



5.2(D) Composite I section with geometric details.

A beam 188 element has been used to mesh the model. It is as shown in the figure 5.3

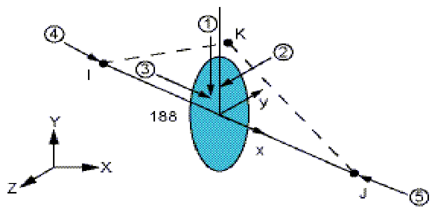


Fig. 5.3 Beam Element

BEAM188 is based on Timoshenko beam theory, which is a first-order shear-deformation theory: transverse-shear strain is constant through the cross-section (that is, cross-sections remain plane and undistorted after deformation). The element can be used for slender or stout beams. Due to the limitations of first-order shear-deformation theory, slender to moderately thick beams can be analyzed. Use the slenderness ratio of a beam structure. For both types of sections, beam 188 element has been used.

Table 5.1 Details of meshing

Sr.No.	Model	Node	Element
1	I section	853	854
2	Composite I section	86	88

Material properties used in analysis are given table 5.2.

Table 5.2 Material properties

Sr. No	Materials	Steel	Concrete
1	Modules of Elasticity in N/mm^2	200 000	22 361
2	Poisson's ratio	0.3	0.28
3	Density Kg/mm^3	7850 E-9	2400 E-9
4	Coefficient of Thermal Expansion (aplx) mm/mm ^{0}C	12 E-6	8 E -6

2D coupled field analysis is carried out. In boundary conditions, degrees of freedom are made zero in Y-direction at the bottom of truss member as shown in figure 1.1. Temperature is applied on each link of truss member and corresponding values of strain and deflection are derived. Temperature r is varied with range 100^{0}C – 150^{0}C and corresponding results are plotted as shown below.

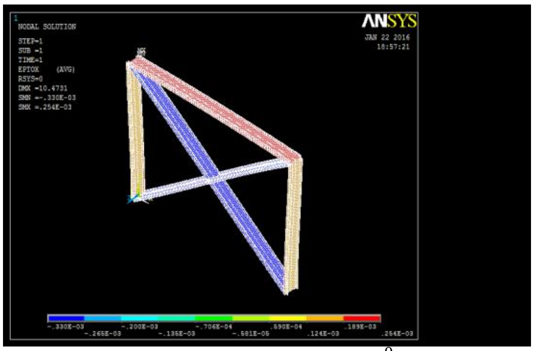


Fig. 5.4 Response at 100^{0}C

Fig.5.4 shows the response at temperature 100^{0}C and values of strain and deformations at temperature 100^{0}C.when the steel frame is unprotected that is only I-section is used for made up of steel frame.

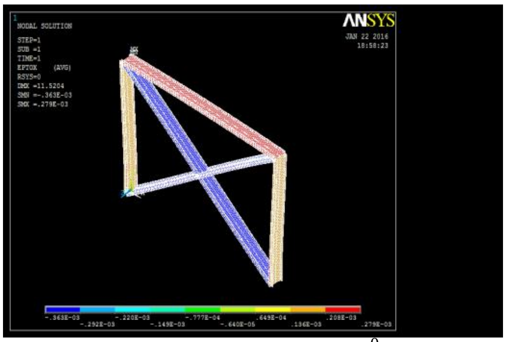


Fig. 5.5 Response at 110^{0}C

Fig.5.5 shows the response at temperature 110^{0}C and values of strain and deformations at temperature 110^{0}C.when the steel frame is unprotected that is only I-section is used for made up of steel frame.

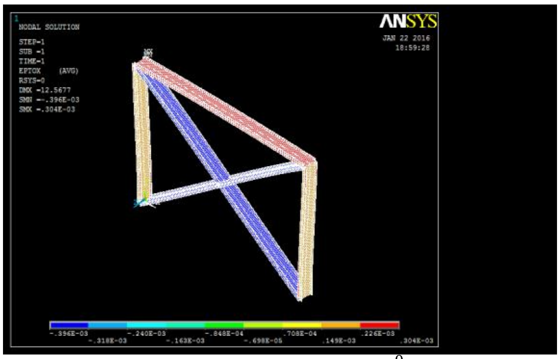


Fig. 5.6 Response at 120^{0}C

Fig.5.6 shows the response at temperature 120^{0}C and values of strain and deformations at temperature 120^{0}C.when the steel frame is unprotected that is only I-section is used for made up of steel frame.

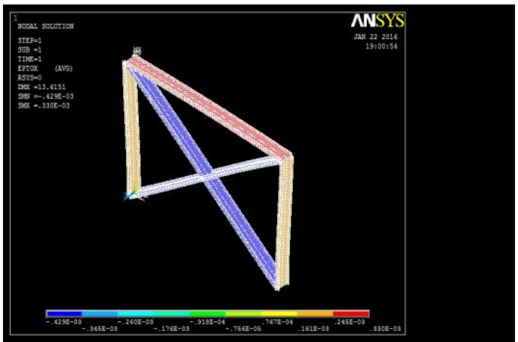


Fig. 5.7 Response at 130^{0}C

Fig.5.7 shows the response at temperature 130^{0}C and values of strain and deformations at temperature 130^{0}C.when the steel frame is unprotected that is only I-section is used for made up of steel frame.

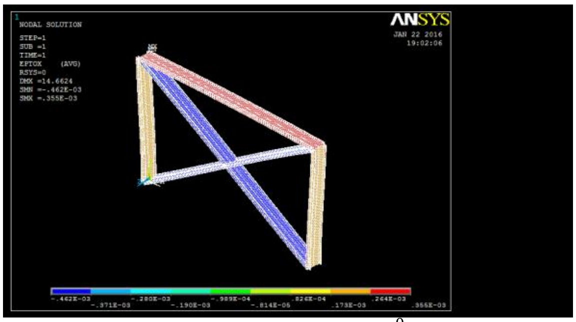


Fig. 5.8 Response at 140^{0}C

Fig.5.8 shows the response at temperature 140^0C and values of strain and deformations at temperature 140^0C.when the steel frame is unprotected that is only I-section is used for made up of steel frame.

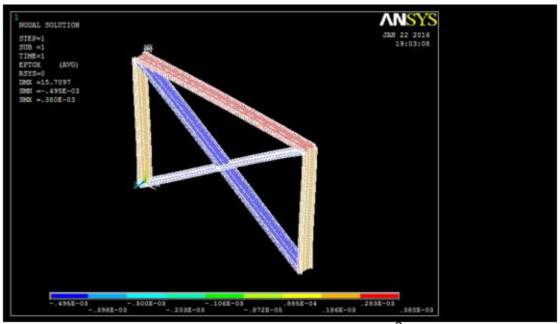


Fig. 5.9 Response at 150^0C

Fig.5.9 shows the response at temperature 150^0C and values of strain and deformations at temperature 150^0C.when the steel frame is unprotected that is only I-section is used for made up of steel frame.

Results are tabulated as shown below

Table 5.3 Results of analysis for I section with respect to temperature when it is unprotected

Sr. No.	Temperature	Maximum strain SMX	Deflection DMX
1	100	$0.254x10^{-3}$	10.4731
2	110	$0.279\ x10^{-3}$	11.5204
3	120	$0.304\ x10^{-3}$	12.5677
4	130	$0.330\ x10^{-3}$	13.6151
5	140	$0.355\ x10^{-3}$	14.6624
6	150	$0.380\ x10^{-3}$	15.7057

Similarly, temperature is applied on each link of truss member which has composite I section. Temperature is varied with range 100^0C – 150^0C and corresponding results are plotted as shown below.

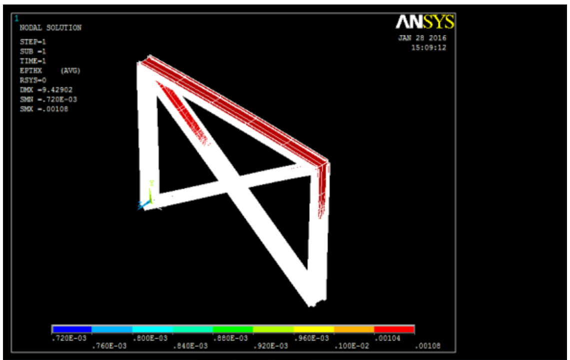


Fig. 5.10 Response at 100^0C

Fig.5.10 shows the response at temperature 100^0C and values of strain and deformations at temperature 100^0C.when the steel frame is protected with insulating material like concrete that is composite I-section is used for made up of steel frame.

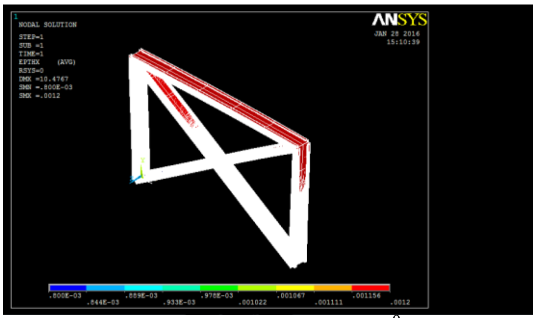


Fig. 5.11 Response at 110^0C

Fig.5.11 shows the response at temperature 110^0C and values of strain and deformations at temperature 110^0C.when the steel frame is protected with insulating material like concrete that is composite I-section is used for made up of steel frame.

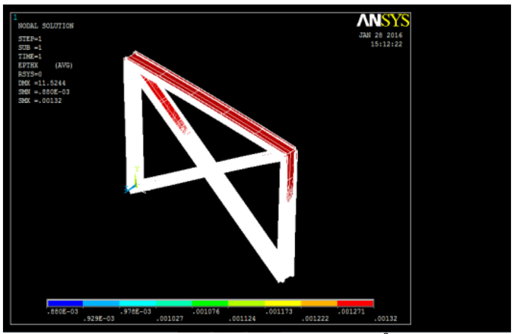


Fig. 5.12 Response at 120^0C

Fig.5.12 shows the response at temperature 120^0C and values of strain and deformations at temperature 120^0C.when the steel frame is protected with insulating material like concrete that is composite I-section is used for made up of steel frame.

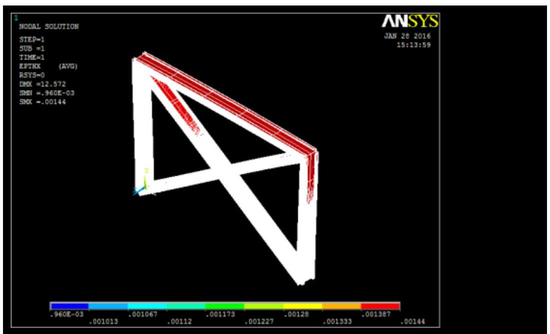


Fig. 5.13 Response at 130^0C

Fig 5.13 shows the response at temperature 130^0C and values of strain and deformations at temperature 130^0C.when the steel frame is protected with insulating material like concrete that is composite I-section is used for made up of steel frame.

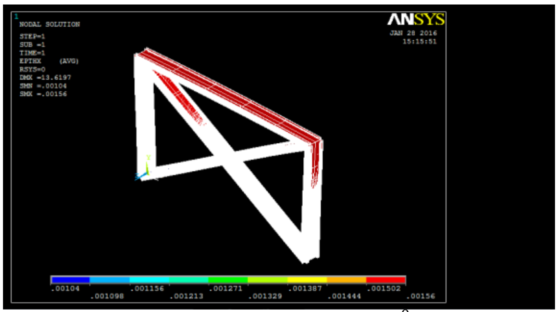


Fig. 5.14 Response at 140^{0}C

Fig.5.14 shows the response at temperature 140^{0}C and values of strain and deformations at temperature 140^{0}C.when the steel frame is protected with insulating material like concrete that is composite I-section is used for made up of steel frame.

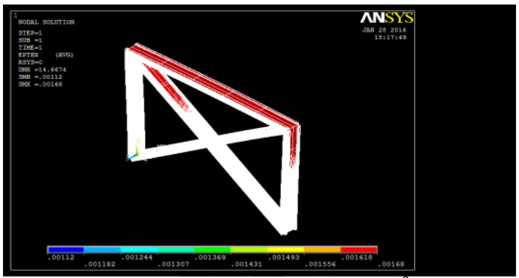


Fig. 5.15 Response at 150^{0}C

Fig.5.15 shows the response at temperature 150^{0}C and values of strain and deformations at temperature 150^{0}C.when the steel frame is protected with insulating material like concrete that is composite I-section is used for made up of steel frame.

Results are tabulated as shown below

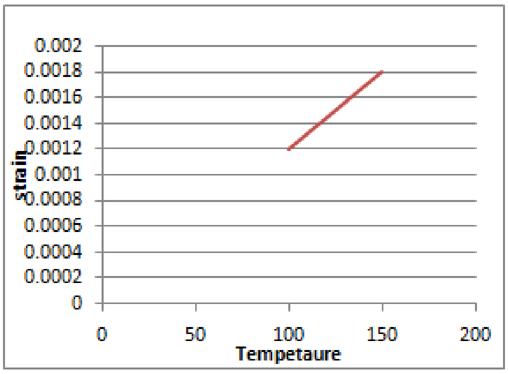
Table 5.4 Results of analysis for composite I section with respect to temperature when it is protected with concrete.

Sr. No	Temperature	SMX	DMX
1	100	0.00012	9.570
2	110	0.000132	10.419
3	120	0.000144	11.655
4	130	0.000156	12.709
5	140	0.000168	13.459
6	150	0.00018	14.515

VI. RESULT AND DISCUSSION:

The results are as shown in below in graphical format:

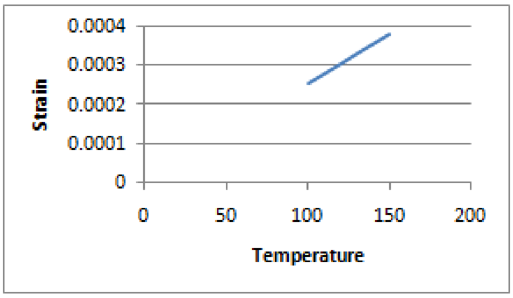
6.1 Results for analytical investigation:



Graph 6.1 Strains vs. Temperature

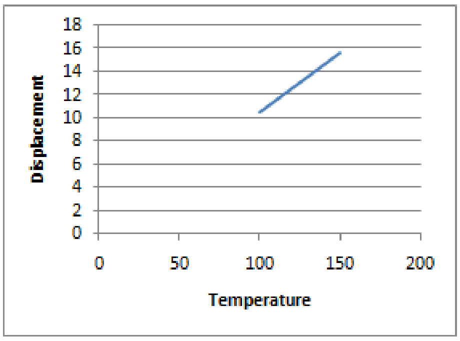
Above graph 6.1 shows strain vs. Temperature relation the value of strain at different elevated temperature having range is 100^{0}c-150^{0}c.As temperature increases strain increases. These values are obtained from the formula in Euro-code 3.

6.2 Result of steel frame when it is unprotected is as shown below:



Graph 6.2 Strains vs. Temperature

Above graph 6.2 shows strain vs. Temperature relation the value of strain at different elevated temperature having range is 100^{0}c-150^{0}c When Steel Frame is Unprotected. As temperature increases strain increases. These values are obtained from the ANSYS Software.

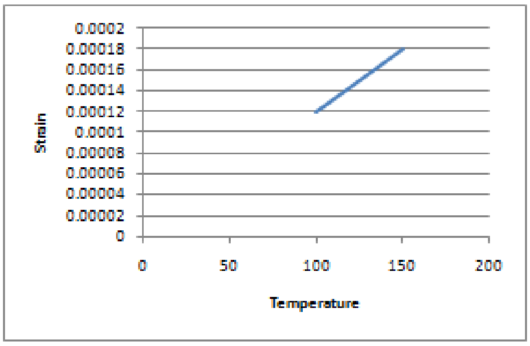


Graph 6.3 Displacements vs. Temperature

Above graph 6.3 shows Displacement vs. Temperature relation the value of Displacement at different elevated temperature having range is

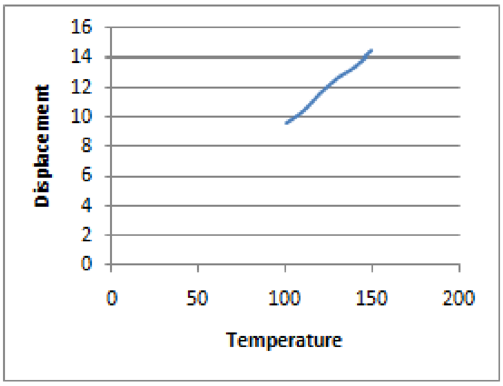
100^0c-150^0c When Steel Frame is unprotected .As temperature increases Displacement increases. These values are obtained from the ANSYS Software.

6.3 Result of steel frame when it is protected with concrete is as shown below:



Graph 6.4 Strains vs. Temperature

Above graph 6.4 shows strain vs. Temperature relation the value of strain at different elevated temperature having range is 100^0c-150^0c When Steel Frame is protected with concrete. As temperature increases strain increases. These values are obtained from the ANSYS Software.



Graph 6.5 Displacements vs. Temperature

Above graph 6.5 shows Displacement vs. Temperature relation the value of Displacement at different elevated temperature having range is 100^0c-150^0c When Steel Frame is protected with concrete. As temperature increases Displacement increases. These values are obtained from the ANSYS Software

VII. CONCLUSION

Based on the studies so far carried out the following conclusions can be drawn.

1. From the above study it can be concluded that as temperature increases strains are increases when steel is unprotected but when steel is protected with material like concrete then the value of strain is reduced by 57.48% and the values are shown in table 7.1 below.

Strain			
Sr.No.	**Unprotected**	**protected**	**% reduction**
1	$0.254\text{x}10^{-3}$	0.000108	57.48
2	$0.279\ \text{x}10^{-3}$	0.000120	56.57
3	$0.304\ \text{x}10^{-3}$	0.000132	56.63
4	$0.330\ \text{x}10^{-3}$	0.000144	56.36
5	$0.355\ \text{x}10^{-3}$	0.000156	56.05
6	$0.380\ \text{x}10^{-3}$	0.000168	55.78

2. From the above study it can be also concluded that as temperature increases displacements are increases when steel is unprotected but when steel is protected with material like concrete then the value of displacement is reduced by 9.96% and the values are shown in table 7.2 below.

Displacement			
Sr.No.	**Unprotected**	**protected**	**% reduction**
1	10.4731	9.4290	9.96
2	11.5204	10.4767	9.05
3	12.5677	11.5244	8.30
4	13.6151	12.5720	7.66
5	14.6624	13.6197	7.11
6	15.7057	14.6674	6.61

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