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Analysis of Loaded Structural Steel Members Under Thermal Loading

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***Abstract*— In this paper, structural and modal analysis of Structural carbon steel member with point load under thermal loading is studied. Theoretical calculations for deflection and stress of cantilever member and member with both end fixed are carried out. Effect of different cross section member with same cross section area on deflection and stress is also studied. During mechanical loading, the effect of thermal stresses and deformations on the performance of structural members due to change in temperature during restrained condition is generally not considered while designing structure. Most of the mechanical components are subjected to thermal variation. This paper describes the behavior of structure when subjected to variable temperature. The change in temperature makes material to expand and if this expansion is restrained, stresses are induced which affect expected performance of structure. In restrained condition, very large force is generated and its ignorance can lead to unsafe design. When structure is subjected to high temperature, it results in reduction in stiffness and strength which significantly affects the structural performance. The primary objective of this project work is to check the effect of temperature variation on deflection and stress of loaded beam. FEA analysis is carried out with the help of ANSYS and results are compared with actual experimentation. Also an attempt is made to study effect of temperature on mode shape and modal frequency of structural member.**

***Keywords*— Deflection, Mode, Mode shape, Modal analysis. Restrained condition, Stress, Temperature Load, Thermal expansion,**

NOMENCLATURE

σ = Uniaxial Stress, MPa
P = Load, N
A = Area of Cross section, mm2
T = Temperature, ^{0}C
α = Coefficient of thermal expansion , /^{0}C
E = Young's Modulus, GPa
δ = Deflection, mm
μ = Poisson's Ratio
ϱ = Density, Kg/m^3
Є = Temperature Strain
y_m = Lateral deflection due to temperature change, mm
I = Moment of Inertia, mm^4
L = Length , mm
b = Breadth, mm
h = Height, mm

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I. INTRODUCTION

Most of the mechanical components are subjected to temperature variation. Temperature variation causes expansion or contraction of the member. If member expansion is restrained then thermal stresses are developed. High temperature causes loss of strength and stiffness which weaken the structure. Response of member to combined thermal and mechanical loading for different types of restrains is studied which is helpful in understanding the behavior of mechanical structure [7]. Analysis of member subjected to mechanical and thermal loading is done. Structural carbon Steel (ASME SA36) [9] is selected to study the effect of thermal loading on mechanically loaded member with different types of restraining support condition is studied. In this project, theoretical calculations for deflection & slope of cantilever and simply supported beam with point load under thermal loading are studied. Effect of temperature variation on deflection and slope of loaded beam is studied. FEA analysis is carried out with the help of ANSYS [5]

Most situations in real structures under temperature variation have a complex mix of mechanical strains due to applied loading and mechanical strains due to restrained thermal expansion. All analytical expressions developed using concepts in fundamental structural mechanics [4]. The most fundamental relationship that governs The behavior of structures when subjected to thermal effects is governed by relationship

$$Є_{Total} = Є_{Thermal} + Є_{Mechanical} \quad (1)$$

Total strain in structural member is the summation of thermal strain and mechanical strain. The stress in structure depends only on mechanical strain. Thermal stress will be developed only when thermal strains are fully restrained. Mechanical stress will depend upon the cross section of the member. To check the effect of cross section on the bending stress rectangular and I- section member with same cross sectional area 80 mm^2 is considered.

II. OBJECTIVES

Objectives of this study are

1) Study of temperature effect on the loaded cantilever and Fixed member for rectangular and I-section

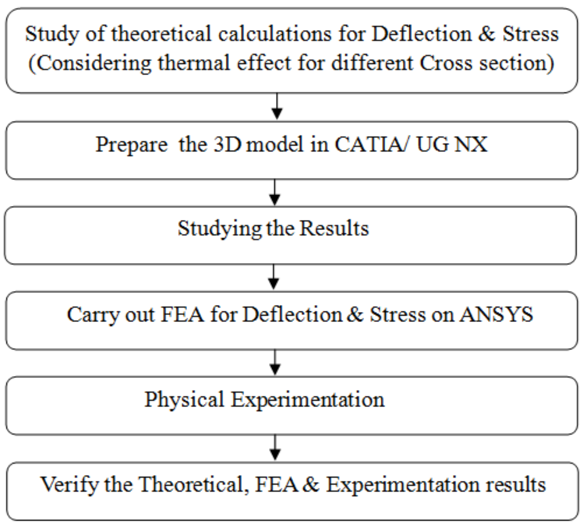
2) Calculation of Stress and deflection in loaded member at different temperature (20^0C, 200^0C, 300^0C, 400^0C and 500^0C) considering combined effect of mechanical and thermal factor.

3) Study of effect of different cross section having same cross sectional area on stress and deflection.

4) Compare the theoretical & Analysis result with actual experimentation.

5) Study the effect of temperature on natural frequency and mode shape using ANSYS.

III. METHODOLOGY



IV. FORMULATION

Material Specification

Material : Structural Carbon Steel. ASME SA36. [9]

Young's Modulus (E) = 200 GPa

Poisson's Ratio (μ) = 0.26

Density (ϱ) = 7850 Kg/m^3

Tensile Strength = 400-500 MPa

Yield point Strength = 250 MPa

Coefficient of Thermal Expansion (α) = $12\text{x}10^{-6}$ /^{0}C

Temperature (^{0}C)	20	100	200	300	400	500
Young's Modulus (GPa)	200	200	189	168	147	126

Formulae for calculation of Moment of Inertia and deflection, design books are used [1],[2].

1) Moment of Inertia calculation for rectangular and I-Section

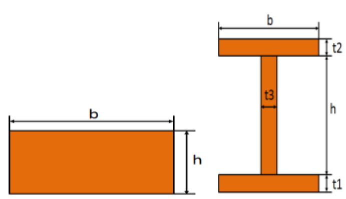


Fig. 1. Rectangular and I-Section

a) Rectangular Section

$$I = \frac{bh^3}{12} \quad (2)$$

b) I-Section

$$I = \frac{bd^3}{12} - \frac{(b-t3)(d-2t1)^3}{12} \quad (3)$$

2) Stress and deflection due to temperature change

a) Cantilever Member

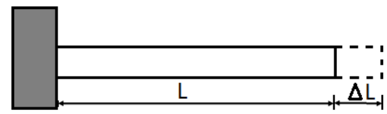


Fig.2. Thermal expansion of Cantilever member

Change in the dimensions of cantilever member due to increase in temperature is given below

Change in length (ΔL) = αLΔT mm (4)

New length (Le) = L+ ΔL = L(1+αΔT) mm (5)

New breadth (be) = b + Δb = b(1+αΔT) mm (6)

New Height (he) = h + Δh = h(1+αΔT) mm (7)

Stress does not induce in member because of free expansion

b) Fixed member

For fixed member, axial expansion is zero. Which induces thermal stress inside body because of restraining force. Thermal stress causes lateral deflection similar to buckling [3]. Lateral deflection is calculated using relation

$$\text{Lateral deflection } (y_m) = \frac{2L}{\pi}\sqrt{\epsilon + \frac{\epsilon^2}{2}} \quad \text{mm} \quad (8)$$

Temperature Strain (Є) = α ΔT (9)

Restraining Force = EAαΔT (10)

Axial Stress = EαΔT (11)

3) Stress and Deflection of member with point load

a) Cantilever member

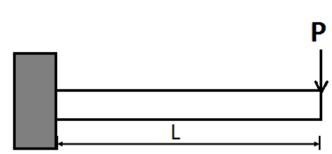


Fig. 3. Cantilever member

$$\text{Deflection } (\delta) = \frac{PL^3}{3EI} \quad \text{mm} \quad (12)$$

$$\text{Bending Stress } (\sigma_b) = \frac{My}{I} \quad \text{MPa} \quad (13)$$

b) Fixed Member

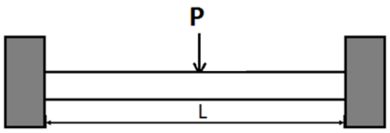


Fig. 4. Fixed Member

$$\text{Deflection } (\delta) = \frac{PL^3}{192EI} \quad \text{mm} \tag{14}$$

$$\text{Bending Stress} = \frac{My}{I} \quad \text{MPa} \tag{15}$$

4) Combined Mechanical and thermal loading

$$\epsilon_{total} = \epsilon_{thermal} + \epsilon_{mechanical} \tag{16}$$

Illustration 1:

Let us consider Structural Carbon Steel (ASME SA36) member with point load of 1000 N. Length is 400 mm and cross sectional area= 80 mm^2

Calculate the stress and deflection in the member at different temperature (20^{0}C, 200^{0}C, 300^{0}C, 400^{0}C, 500^{0}C) for

1) Cantilever member with Rectangular section
2) Cantilever member with I- section
3) Fixed member with Rectangular section
4) Fixed member with I-section

Rectangular Section: b=40 mm, h= 20 mm.

I-Section: b=46 mm, h=70 mm, t1=t2=5.2 mm, t3=4.6 mm

Using all expressions in the section IV, Calculations are carried out and results are tabulated

Table 1. Cantilever Member with Rectangular Section

Temperature	^{0}C	20	200	300	400	500
Young's Modulus (E)	MPa	200000	189000	168000	147000	126000
Length (Le)	mm	400	400.864	401.344	401.824	402.304
Width (be)	mm	40	40.0864	40.1344	40.1824	40.2304
Height (he)	mm	20	20.0432	20.0672	20.0912	20.1152
y	mm	10	10.0216	10.0336	10.0456	10.0576
Bending Moment (M)	N-mm	400000	400864	401344	401824	402304
Moment of Inertia (I)	mm^4	26666.67	26897.81	27026.88	27156.4	27286.4
Deflection (δ)	mm	4	4.223681	4.745958	5.417473	6.312844
Bending Stress (σb)	MPa	150	149.3541	148.9971	148.6413	148.2868

Table 2. Cantilever Member with I- Section

Temperature	^{0}C	20	200	300	400	500
Young's Modulus (E)	MPa	200000	189000	168000	147000	126000
Length (Le)	mm	400	400.864	401.344	401.824	402.304
Flange Width (be)	mm	46	46.09936	46.15456	46.20976	46.26496
Web Height (he)	mm	70	70.1512	70.2352	70.3192	70.4032
Flange thickness (t1e = t2e)	mm	5.2	5.211232	5.217472	5.223712	5.229952
Web thickness (t3e)	mm	4.6	4.609936	4.615456	4.620976	4.626496
Total Depth (de)	mm	80.4	80.57366	80.67014	80.76662	80.8631
y	mm	40.2	40.28683	40.33507	40.38331	40.43155
Bending Moment (M)	N-mm	400000	400864	401344	401824	402304
Moment of Inertia (I)	mm^4	808904.1	815915.7	819830.7	823759.8	827702.9
Deflection (δ)	mm	0.131866	0.13924	0.156457	0.178595	0.208112
Bending Stress (σb)	MPa	19.87875	19.79315	19.74583	19.69869	19.65171

Table 3. Fixed Member with Rectangular Section

Temperature	^{0}C	20	200	300	400	500
Young's Modulus (E)	MPa	200000	189000	168000	147000	126000
Length (Le)	mm	400	400	400	400	400
Width (be)	mm	40	40.0864	40.1344	40.1824	40.2304
Height (he)	mm	20	20.0432	20.0672	20.0912	20.1152
y	mm	10	10.0216	10.0336	10.0456	10.0576
Bending Moment (M)	N-mm	50000	50000	50000	50000	50000
Moment of Inertia (I)	mm^4	26666.67	26897.81	27026.88	27156.40	27286.40
Deflection due to point load (δ)	mm	0.063	0.066	0.073	0.084	0.097
Bending Stress (σb)	MPa	18.75	18.63	18.56	18.50	18.43
Temperature strain (ϵ_T)		0	0.00216	0.00336	0.00456	0.00576
Restraining force	N	0.00	328004.40	454623.74	541157.81	587315.87
Uniform Axial Stress	MPa	0	408.24	564.48	670.32	725.76
Mid span deflection due to ΔT	mm	0.00	11.85	14.78	17.22	19.36
Total Deflection (δ_T)	mm	0.06	11.91	14.85	17.31	19.46

Table 4. Fixed member with I-Section

Temperature	^{0}C	20	200	300	400	500
Young's Modulus (E)	MPa	200000	189000	168000	147000	126000
Length (Le)	mm	400	400	400	400	400
Flange Width (be)	mm	46.000	46.099	46.155	46.210	46.265
Web Height (he)	mm	70.000	70.151	70.235	70.319	70.403
Flange thickness (t1e = t2e)	mm	5.200	5.211	5.217	5.224	5.230
Web thickness (t3e)	mm	4.600	4.610	4.615	4.621	4.626
Total Depth (de)	mm	80.400	80.574	80.670	80.767	80.863
Area (A)	mm	800.400	803.861	805.788	807.716	809.647
y	mm	40.200	40.287	40.335	40.383	40.432
Bending Moment (M)	N-mm	50000	50000	50000	50000	50000
Moment of Inertia (I)	mm^4	808904.112	815915.720	819830.699	823759.750	827702.907
Deflection (δ)	mm	0.002	0.002	0.002	0.003	0.003
Bending Stress (σb)	MPa	2.485	2.469	2.460	2.451	2.442
Temperature strain (ϵ_T)		0	0.00216	0.00336	0.00456	0.00576
Restraining force	N	0.000	328168.403	454851.055	541428.384	587609.525
Uniform Axial Stress	MPa	0.000	408.240	564.480	670.320	725.760
Mid span deflection due to ΔT	mm	0.000	11.847	14.781	17.224	19.364
Total Deflection (δ_T)	mm	0.002	11.850	14.783	17.227	19.367

Analysis Results for Cantilever member with rectangular and I-Section are given below.

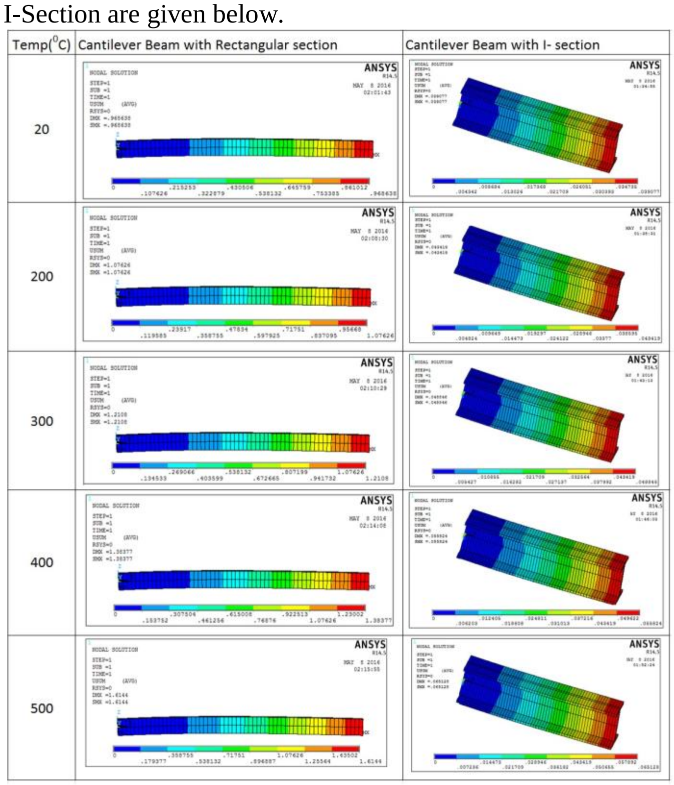


Fig. 5. Deflection of Cantilever member with rectangular & I-section

V. EXPERIMENTATION

Experimentation will be conducted for below combinations with same load of 1000N

1) Cantilever member with rectangular section
2) Cantilever member with I- section
3) Fixed member with rectangular section
4) Fixed member with I- section

Test specimen

Test specimen details are shown below. Testing length of specimen is 400 mm. To hold the specimen, additional length of 50 mm provided, which is referred as holding length.

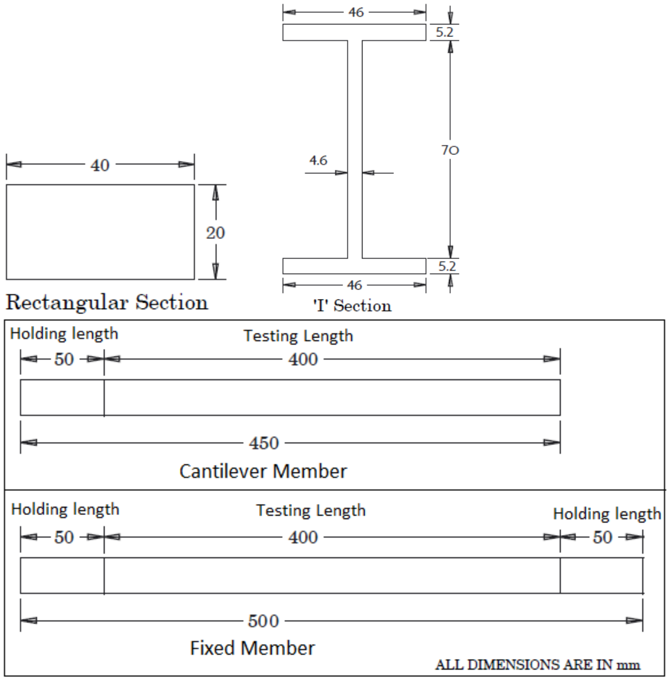


Fig. 6. Test Specimen

Test Set-Up

Proposed test set up consist of testing member, strain gauge, Load attachment, pointer for deflection measurement. Set up shows rectangular section member. From I-section member similar set up will be used. Cantilever and Fixed member will be tested at different temperature (20^{0}C, 200^{0}C, 300^{0}C, 400^{0}C, 500^{0}C) with same point load of 1000N.

1) Cantilever Member

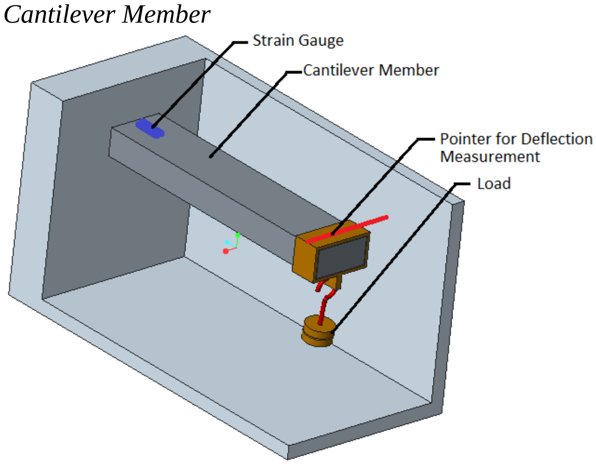


Fig. 7. Cantilever Member Test setup

2) Fixed member

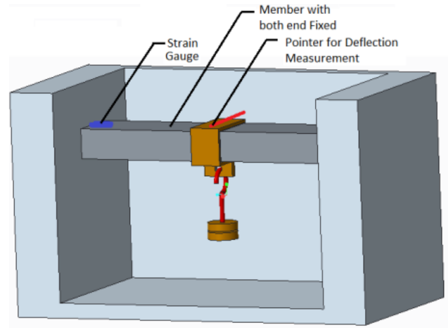


Fig. 8. Fixed Member Test setup

VI. MODAL ANALYSIS

Modal analysis is done using ANSYS R14.5. Effect of temperature on mode shape and modal frequency for cantilever member with rectangular and I section is studied

1) Cantilever Member with Rectangular Section

Table 5. Modal Analysis result for Cantilever Member with Rectangular Section

Mode	Frequency (Hz)					
	20^{0}C	100^{0}C	200^{0}C	300^{0}C	400^{0}C	500^{0}C
1	102.19	102.19	98.68	93.04	87.03	80.57
2	202.89	202.89	196.52	185.28	173.31	160.46
3	633.10	633.10	604.68	570.10	533.28	493.72
4	1216.90	1216.90	1176.20	1109.00	1037.40	960.40
5	1465.00	1465.00	1445.20	1362.60	1274.60	1180.00
6	1741.90	1741.90	1637.80	1544.20	1444.40	1337.30

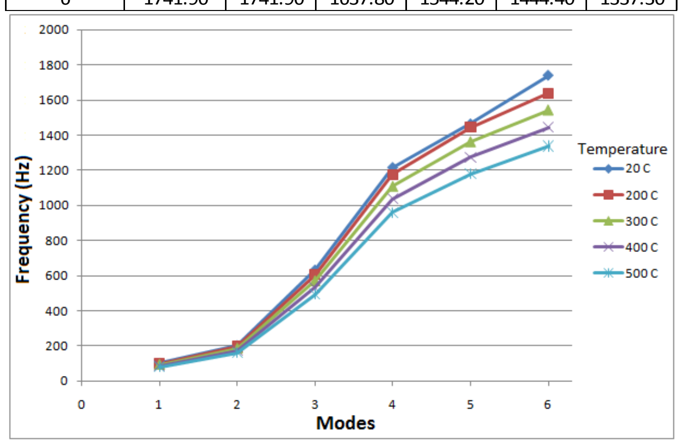


Fig. 9. Graph between Modes and Frequency

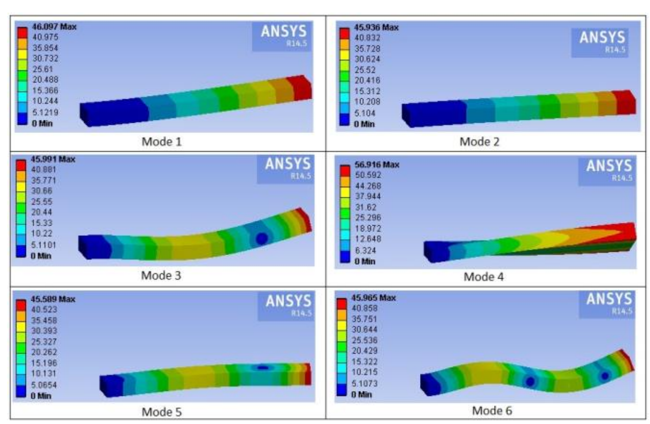


Fig. 10. Modal Analysis for Cantilever member with rectangular section

2) Cantilever Member with I- Section

Table 6. Modal Analysis result for Cantilever Member with I-Section

Mode	Frequency (Hz)					
	20^{0}C	100^{0}C	200^{0}C	300^{0}C	400^{0}C	500^{0}C
1	239.70	239.70	227.40	214.40	200.55	185.67
2	326.70	326.70	309.94	292.21	273.34	253.06
3	719.76	719.76	682.83	643.78	602.20	557.53
4	875.11	875.11	830.20	782.72	732.17	677.85
5	1201.80	1201.80	1140.10	1074.90	1000.50	930.91
6	1687.10	1687.10	1600.60	1509.00	1411.60	1306.80

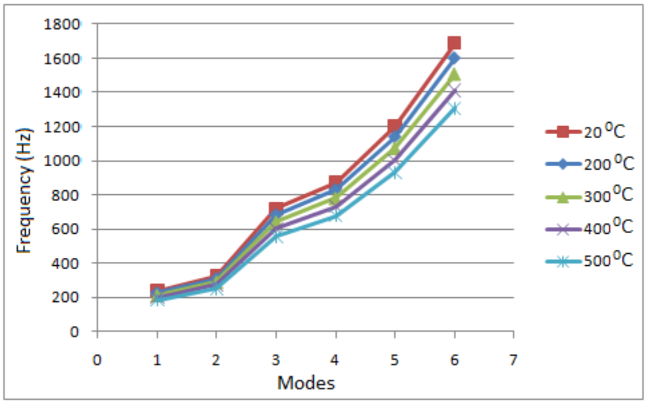


Fig. 11. Graph between Modes and Frequency

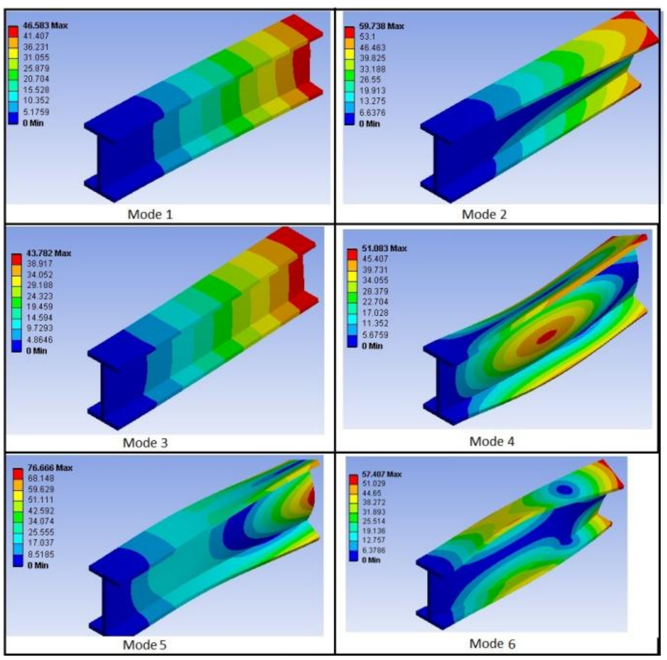


Fig. 12. Modal Analysis for Cantilever member with I-section

VII. Results and Discussions

The results for stress and deflection are tabulated in Section IV. Graph for temperature Vs Deflection is plotted.

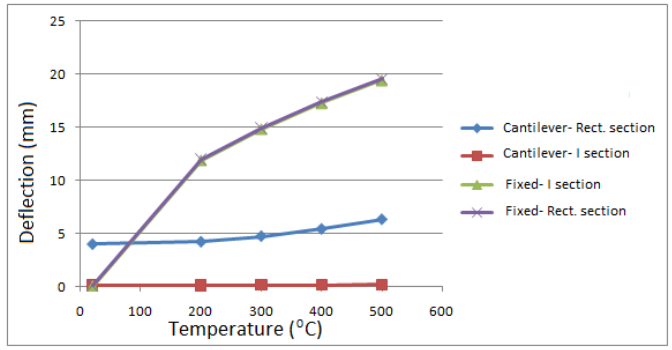


Fig. 13 Temperature Vs Deflection Graph

A] Cantilever Member

1. In case of Cantilever member, allows expansion of beam along its length freely. Hence no stresses are induced due to temperature change

2 Overall deflection is increased because of loss of strength and stiffness because of temperature change

3. Deflection in Rectangular section is approximately 30 times that of I-section member for same cross sectional are

4. Bending Stress in Rectangular section is approximately 8 times that of I-section member.

B] Fixed Member

1. In case of Fixed member, Thermal expansion is resisted by producing equal and opposite force P producing uniform axial stress σ , If axial stress continues to increase, it will soon reach to yield stress. And if material is elastic-plastic then beam will continue to yield without increase in yield stress. If beam is slender then it will buckle before reaching yield stress

2 Overall deflection is increased because of loss of strength and stiffness because of temperature change

3. Bending Stress in Rectangular section is approximately 10 times that of I-section member for same cross sectional area.

C] Cantilever member deflects less than fixed member when subjected to combined mechanical and thermal loading.

D) As temperature increases, stiffness of member decreases results in decrease in modal frequency of member

VIII. Conclusion

The Design verification of Structural Carbon Steel members is achieved through numerical calculation, analysis and experimentation. Stress and deflection values shows that structure performance decrease because of increase in temperature. Therefore during design of structural members, combined effect of mechanical and thermal loading must considered. The above study can be useful for designing the wings of aero plane and heat equipment where loaded component is subjected to temperature variation.

Further study can be done for other structural members with different cross sections.

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