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Mechanical Computations of Functionally Graded Material Plate Subjected to Transverse Load

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ABSTRACT

The area of Functionally graded material (FGM) is evolved on the basis of research and demand in materials and mechanics of structures and because of the combined requirements of material and structural components. As the FGMs can be used as replacement of homogeneous materials, it is required to compare the properties of FGMs, isotropic and homogeneous materials. These analysis are concerned with parameters such as stress, deflection and structural issues of FG structures such as plates accounting geometrical and physical nonlinearity and shear deformations. Various methods are used to analyze problems related to plates made of FGM. The present paper is concerned with the study of FGM plate with transverse loading on a square FGM plate. The plate is applied to various end conditions such as supported simply and fixed (clamped) edges. The shear stress and strain in non-dimensional values have been computed for Power-FGM and Sigmoid-FGM for various end conditions with a variation in volume fraction component.

Key words: FGM, Mechanical, Strain, Shear strain

1. INTRODUCTION

Composite materials are evolved in response to demand from technology due to advanced activities in aircrafts, aerospace and automotive industries. These materials have lower specific gravity that makes their properties better in strength to weight ratio and Young's modulus to many traditional engineering materials such as metals. The properties of Functionally graded materials are taken to furnish peculiar requirements of applications in scientific and engineering field. Thus, mechanical, thermal and thermo-mechanical analysis of FGM structure has attracted the attention of researcher. FGM is developed by varying the properties gradually in one or more directions as compared to composites. Properties of FGM is dependent upon volume fraction and hence on the distribution of material. The volume fraction may be varied by no. of laws among which Power law (P-FGM), Sigmoid law (S-FGM) and Exponential law (E-FGM) are the most used laws. Reddy studied FGM plates and used Power law for the material distribution. [1,3]. Lambros and Santare [4] conducted experimental studies for plates made of FGM. Weber [5] and Armelle [10] utilized numerical homogenization techniques for modeling of FGM. Tahani [9] conducted non linear analysis of FGM beams. Sigmoid law was used by Shyang [8] and Bhandari and Purohit[17] since sigmoid law exhibits more uniform variation in volume fraction as compared to Power-FGM. FGMs are used in various geometry forms such as shells, thin plates, thick plates, beams etc. Since a plate exhibits two dimensional behavior, a lot of principles are used by scientists to study FGM plate performance under loadings. Vanam [12] used finite element method for the solution of problems of FGM plates. Theories for shear deformation of the First Order (FSDT) and Third Order (TSDT) are mostly used for analyzing FGM plates. FSDT has been proved useful by Alshorbagy et. al. [15] and shown that FSDT is appropriate for plates of thin category as impact of transverse shear stress is comparatively lesser while TSDT was utilized by Reddy [1]. Ootao [2] presented 3-D stress in unsteady thermal environment by putting partial heating to FGM plate. Further, it has also been observed by Jha [13] that scientists have applied some constraints to plate boundaries e.g. all edges are simply supported (S) by Reddy [1], Sharma et.al. [18] and all edges clamped (C) Bhandari and Purohit [17] and also the combinations have been used. Though experiments and computational work are done on FGM, finite element analysis (FEA) is prominently used. Yoshihiro [6] studied transient thermo elastic problem of functionally graded thick strip due to nonuniform heat supply. Takemasa [7] gave study of two-dimensional elasticity on FGM. Golmakani [11] performed bending analysis considering nonlinearity of FGM plate with annular shape by using higher-order shear deformation plate theory. Hashempoor [16] modeled analytically functionally graded plates under general transverse loads. A no. of ceramic-metal combinations have been utilized as specimen e.g. Yang [14] used Aluminum-Zirconia, Golmakani [11] used Aluminum-Alumina etc. Aluminum (metal) and Zirconia (Ceramic) is mostly put in use as FGM. Moita et. al. [19] implemented FEM on a non-conforming flat triangular plate. Latest software methods have also been proved to be useful in computational analysis.

In this work Al-ZrO_2 is taken as the material for plate made of FGM. The first order shear deformation theory has been used for the computational analysis. A uniformly distributed load is applied to FGM plate and conjunction of supported simply (S), fixed or clamped (C) and free (F) end conditions. The analysis is formulated using finite element method and results for different FGMs are recorded. The results are tabulated and figured in terms of non dimensional parameters e.g. shear stress and strain.

2. METHODOLOGY

2.1 Material: Ceramic and metal are used to make FGM with controlled variation of volume fraction 'n'. Al-Zirconia (Al-ZrO_2) is put in use in which the metal is Aluminum (Al) and the Zirconia (ZrO_2) is ceramic. The physical properties are shown in Table 1.

Table 1: Physical Properties of Aluminum (Al) and Zirconia(ZrO_2)

S.No.	Property	Al	ZrO_2
1	Young's modulus	70×10^9 Pa	151×10^9 Pa
2	Poisson's ratio	0.3	0.3
3	Density	2707 (Kg/m^3)	3000 (Kg/m^3)

2.2 Gradation: The material gradation laws which are used in the present problem are Power and Sigmoid laws. The material volume is found out using the laws and further properties are calculated in the line of the plate thickness. The computation is done for some of the values 'n' in Power law and Sigmoid law FGM.

2.3 Load applied and plate dimensions: Square FG plate of dimension 1mx1m is considered for the analysis here i.e. aspect ratio is taken unity and the plate thickness (h) istaken 0.02m. The mechanical analysis is performed by applying udl (10^6 Pa) on the said plate.

2.4 End conditions: The end conditions are various combinations of supported simply (S), fixed or clamped (C) and free (F) end conditions as in Table 2.

Table 2: Different end conditions

Abb.	End Conditions
(SSSS)	All edges are supported simply
(FFFF)	All edges are fixed
(SFSF)	Alternate edges are supported simply and fixed
(FUFU)	Alternate edges are fixed and unconstrained
(FFUU)	Two edges are fixed and two are unconstrained
(FFSS)	Two edges are fixed and two are supported simply
(SSUU)	Two edges are supported simply and two are unconstrained
(SSSF)	Three edges are supported simply and one is fixed
(SSSU)	Three edges are supported simply and one is unconstrained
(SSFU)	Two edges are supported simply, one is fixed and one is kept unconstrained

2.5 Computation method: A 8 noded SHELL281 (rectangular) finite element is used in finite element model . Each node has 6 degrees of freedom.

The results are shown in terms of non-dimensional shear stress ($\overline{\sigma_{xy}} = \sigma_{xy} / m$) and strain ($e_x$).

Where

σ_{xy} = Shear stress at the geometric center of the plate,

m = Unit pressure intensity (=$10X10^5$ Pa)

3. RESULTS

The results of simulation on a square FGM plate with different end conditions subjected to mechanical udl are depicted. The results are depicted in nondimensionalized shear stress ($\overline{\sigma_{xy}}$) and strain (e_x).

3.1 Non-Dimensional Shear Stress ($\overline{\sigma_{xy}}$)

The values of non-dimensional shear stress ($\overline{\sigma_{xy}}$) for a square plate with certain end conditions with udl are listed in Table 3-4for P-FGM and in Table 5-6 for S-FGM. The shear stress is presented in Figures 1-2 for Power and in Figure 3-4for Sigmoid FGM respectively. Figure 5 shows shear stress for Exponential FGM for different end conditions of the plate.

Table 3: Effect of end conditions on non-dimensionalized shear stress ($\overline{\sigma_{xy}}$) for P-FGM

Power-FGM					
End	n=0	0.1	0.2	0.5	1
(SSSS)	481	511	525	558	592
(FFFF)	128	136	140	149	158
(SFSF)	215	229	235	250	265
(FUFU)	162	172	177	188	200
(FFUU)	549	583	598	636	675
(FFSS)	554	588	604	643	682
(SSUU)	1777	1887	1938	2060	2187
(SSSF)	394	418	430	457	485
(SSSU)	683	725	745	792	840
(SSFU)	311	330	339	360	382

Table 4: Effect of end conditions on non-dimensionalized shear stress ($\overline{\sigma_{xy}}$) for P-FGM

Power-FGM					
End	2	5	10	100	$\propto$
(SSSS)	622	657	671	683	696
(FFFF)	166	175	179	182	185
(SFSF)	278	294	300	306	312
(FUFU)	210	222	226	231	235
(FFUU)	709	749	765	779	794
(FFSS)	716	757	773	787	802
(SSUU)	2297	2427	2478	2524	2572
(SSSF)	509	538	549	560	570
(SSSU)	883	932	952	970	988
(SSFU)	402	424	433	441	450

Table 5: Effect of boundary conditions on non-dimensionalized shear stress $(\overline{\sigma_{xy}})$ for Sigmoid-FGM

Sigmoid-FGM					
End	n=0	0.1	0.2	0.5	1
(SSSS)	481	565	571	583	592
(FFFF)	128	150	152	155	158
(SFSF)	215	253	256	261	265
(FUFU)	162	191	193	197	200
(FFUU)	549	644	651	665	675
(FFSS)	554	651	658	672	682
(SSUU)	1777	2087	2109	2154	2187
(SSSF)	394	463	468	478	485
(SSSU)	683	802	811	828	840
(SSFU)	311	365	369	377	382

Table 6: Effect of boundary conditions on non-dimensionalized shear stress $(\overline{\sigma_{xy}})$ for Sigmoid-FGM

Sigmoid-FGM					
End	2	5	10	100	∝
(SSSS)	595	598	601	605	696
(FFFF)	159	159	160	161	185
(SFSF)	266	268	269	271	312
(FUFU)	201	202	203	204	235
(FFUU)	679	682	686	689	794
(FFSS)	686	689	693	696	802
(SSUU)	2198	2210	2222	2233	2572
(SSSF)	487	490	493	495	570
(SSSU)	845	849	854	858	988
(SSFU)	384	386	389	391	450

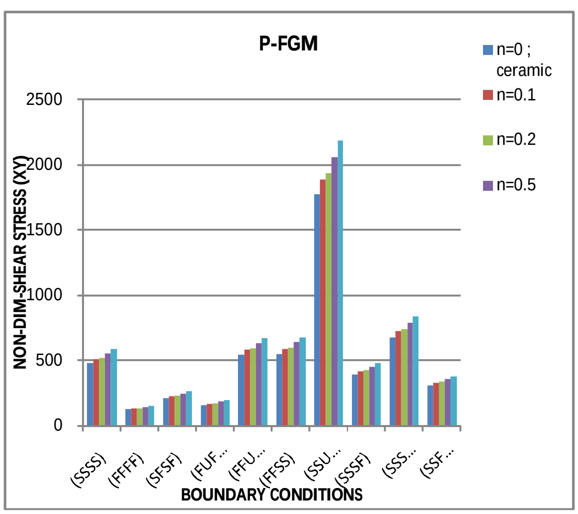

Figure 1: Effect of end conditions on non-dimensionalized shear stress $(\overline{\sigma_{xy}})$ for Power-FGM

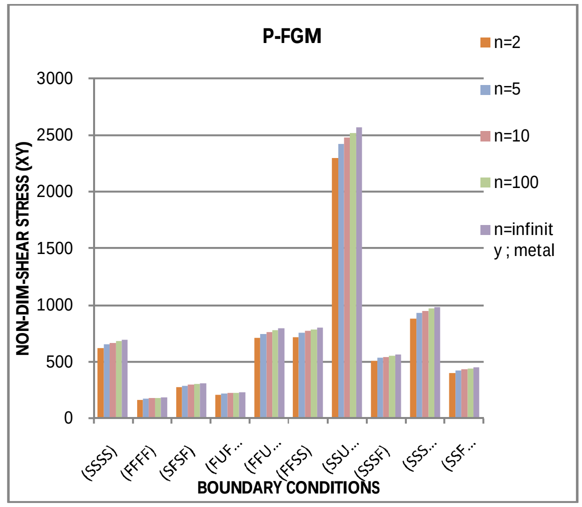

Figure 2: Effect of end conditions on non-dimensionalized shear stress $(\overline{\sigma_{xy}})$ for Power-FGM

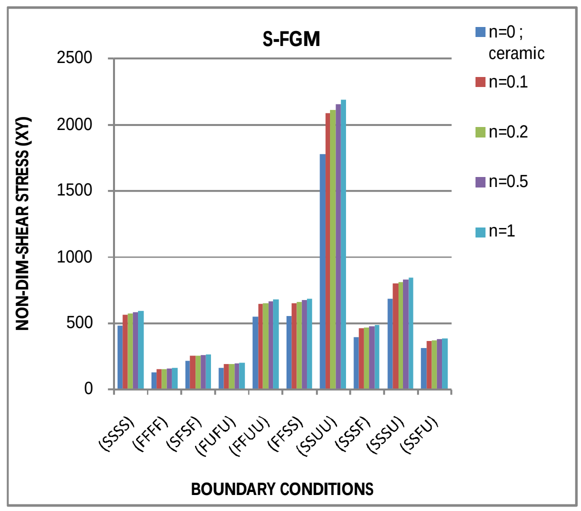

Figure 3: Effect of end conditions on non-dimensionalized shear stress $(\overline{\sigma_{xy}})$ for Sigmoid-FGM

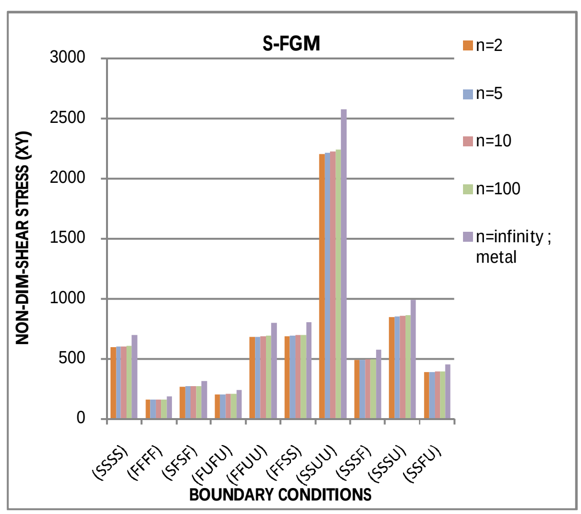

Figure 4: Effect of end conditions on non-dimensionalized shear stress $(\overline{\sigma_{xy}})$ for Sigmoid-FGM

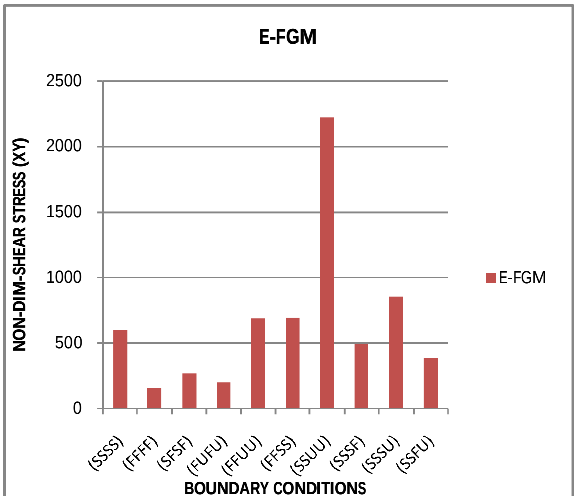

Figure 5: Effect of end conditions on non-dimensionalized shear stress ($\overline{\sigma_{xy}}$) for Sigmoid-FGM

The important points which may be understood from the above tables and figures for non-dimensionalized shear stress ($\overline{\sigma_{xy}}$) are:

(a) The pure ceramic plate has the smallest shear stress ($\overline{\sigma_{xy}}$) among all the end conditions considered here, and the pure metal plate has the maximum shear stress.

(b) Nnondimensionalized shear stress ($\overline{\sigma_{xy}}$)becomes more and more with growing 'n'.Shear stress is 481.7 for ceramic while itbecomes 696 for metal when we look at the SSSS edge condition. This is because of the fact that the stiffness in bending is maximum for ceramic and metal has got minimum.

(c) When it is compared for the different boundary conditions, it is worthnoting that maximum nondimensionalized shear stress ($\overline{\sigma_{xy}}$) is computed for simply supported - free (SSFF) which is 2572 and the minimum is 128 of fixed (clamped) (CCCC) ends.

3.2 Longitudinal Strain (e_x)

The values of strain (e_x) for various end conditions of a FGM plate (1mx1m) udl are listed in Table 7-8for Power-FGM and in Table 9-10 for Sigmoid-FGM. Figures 6-7 show the strain (e_x) variation for Power FGM and Figures 8-9 show the strain (e_x) variation for Sigmoid FGM for some of the end conditions. Figures 10 shows the strain (e_x) variation for Exponential FGM. The results are tabulated for various values of volume fraction 'n' for both the volume fraction laws.

Table 7: Effect of end conditions on strain (e_x x 103) for P-FGM

Power-FGM					
BC	n=0	0.1	0.2	0.5	1
(SSSS)	3.37	3.58	3.69	3.95	4.24
(FFFF)	0.57	0.61	0.63	0.67	0.72
(SFSF)	1.47	1.56	1.61	1.72	1.85
(FUFU)	10.19	10.84	11.15	11.94	12.81
(FFUU)	33.49	35.64	36.67	39.26	42.12
(FFSS)	30.77	32.74	33.69	36.07	38.69
(SSUU)	11.63	12.37	12.73	13.63	14.63
(SSSF)	2.28	2.42	2.49	2.67	2.87
(SSSU)	11.06	11.77	12.11	12.97	13.91
(SSFU)	15.6	16.6	17.08	18.28	19.62

Table 8: Effect of end conditions on strain (e_x x 103) for P-FGM

Power -FGM					
BC	2	5	10	100	∝
(SSSS)	4.54	5.02	5.54	6.44	7.27
(FFFF)	0.77	0.85	0.94	1.09	1.23
(SFSF)	1.98	2.19	2.42	2.81	3.17
(FUFU)	13.72	15.2	16.75	19.47	21.98
(FFUU)	45.12	49.96	55.05	64.03	72.25
(FFSS)	41.45	45.89	50.57	58.82	66.37
(SSUU)	15.67	17.35	19.12	22.23	25.09
(SSSF)	3.07	3.4	3.75	4.36	4.92
(SSSU)	14.9	16.5	18.18	21.15	23.86
(SSFU)	21.01	23.27	25.64	29.82	33.65

Table 9: Effect of end conditions on strain (e_x x 10^3) for S-FGM

Sigmoid-FGM					
BC	n=0	0.1	0.2	0.5	1
(SSSS)	3.37	4.1	4.14	4.19	4.24
(FFFF)	0.57	0.7	0.7	0.71	0.72
(SFSF)	1.47	1.79	1.81	1.83	1.85
(FUFU)	10.19	12.4	12.53	12.67	12.81
(FFUU)	33.49	40.75	41.2	41.66	42.12
(FFSS)	30.77	37.44	37.85	38.27	38.69
(SSUU)	11.63	14.15	14.31	14.47	14.63
(SSSF)	2.28	2.77	2.8	2.83	2.87
(SSSU)	11.06	13.46	13.61	13.76	13.91
(SSFU)	15.6	18.98	19.19	19.4	19.62

Table 10: Effect of end conditions on strain (e_x x 10^3) for S-FGM

Sigmoid-FGM					
BC	2	5	10	100	∝
(SSSS)	4.26	4.3	4.4	4.45	7.27
(FFFF)	0.72	0.73	0.75	0.75	1.23
(SFSF)	1.86	1.88	1.92	1.94	3.17
(FUFU)	12.89	13.01	13.3	13.45	21.98
(FFUU)	42.36	42.78	43.71	44.21	72.25
(FFSS)	38.91	39.3	40.16	40.61	66.37
(SSUU)	14.71	14.85	15.18	15.35	25.09
(SSSF)	2.88	2.91	2.97	3.01	4.92
(SSSU)	13.99	14.13	14.44	14.6	23.86
(SSFU)	19.73	19.92	20.36	20.59	33.65

When comparison is made in Figures 3 and 4, the following points are worthnoting:

(a) Pure ceramic has lowest strain (e_x) while looking at all ends and pure metal has gotlargest.

(b) Comparison of maximum strain for fixed (clamped)-free (CCFF) end condition between Power-FGM and Sigmoid-FGM, shows that for Sigmoid FGM provides smoother change in strain and Power-FGM provides direct dependence on increasing value of 'n'. At 'n' equal to infinity i.e. pure metal, sudden jump in the strain is observed.

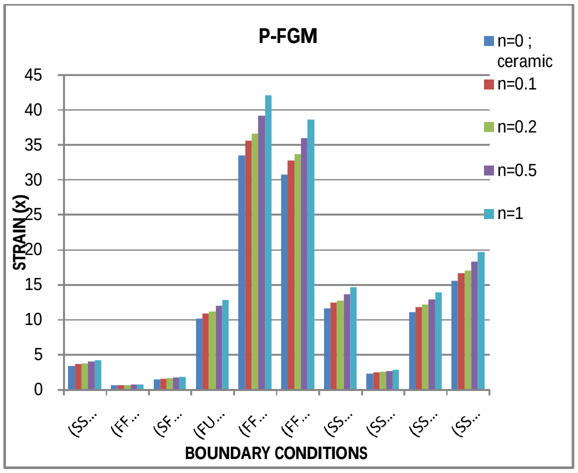

Figure 6: Effect of end conditions on strain (e_x) for P-FGM

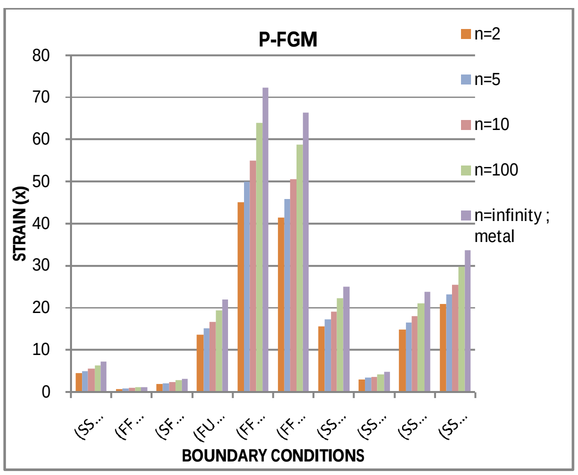

Figure 7: Effect of end conditions on strain (e_x) for P-FGM

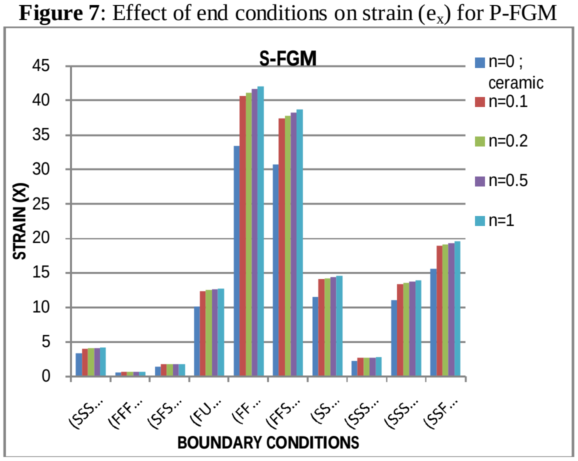

Figure 8: Effect of end conditions on strain (e_x) for S-FGM

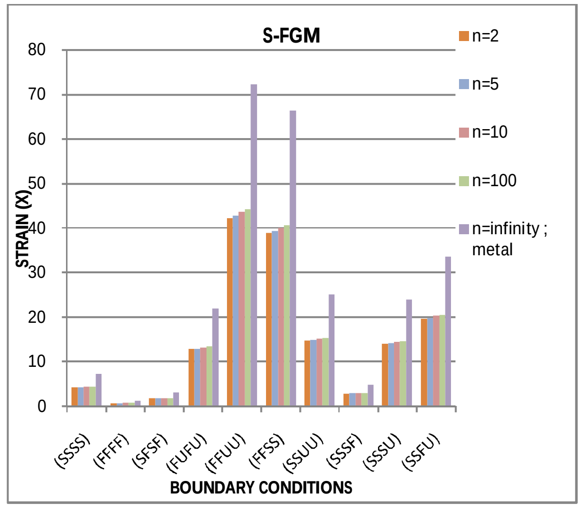

Figure 9: Effect of end conditions on strain (e_x) for S-FGM

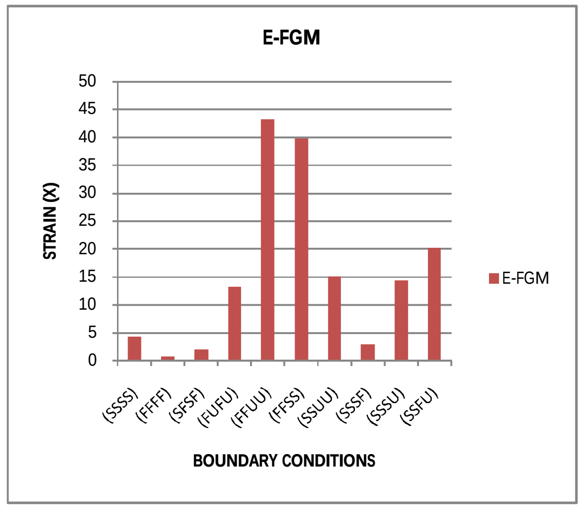

Figure 10: Effect of end conditions on non-dimensional shear stress ($\overline{\sigma_{xy}}$) for Sigmoid-FGM

(d) The largest strain (e_x) is obtained for (CCFF) endsit is 0.072 for metal and 0.032 for ceramic plate. Second highest value of strain (e_x) is obtained for CCSS boundary condition while the minimum strain (e_x) is obtained in the case of fixed (clamped-CCCC) end condition amongst all the end conditions considered here.

4. CONCLUSION AND FUTURE SCOPE

An FGM plate under transverse udl was studied and parametric study was performed for some end conditions. The worthnoting points about the nondimesionalized parameters are as follows

a. Nondimensionalized shear stress and strain for the two FGM's are in between that of ceramic and metal.
b. SSFF end conditions gives the maximum nondimensionalized shear stress ($\overline{\sigma_{xy}}$) and all edges fixed (CCCC) end conditions gives lowest one.
c. The strain (ex) grows with 'n' because of bending strength is the largest for pure plate(ceramic), while the lowest for pure plate of metal.

The work may be extended further with plate aspect ratio and variation in type of load such as point load and also thermomechanical load.

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