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Creation of Computer Based Model for Evaluation of Thermal Equivalence to Normal Stress in Ferrous Material

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Abstract

The Structural components in metallic structures subjected to mechanical loading as well as Thermal loading in severe environmental conditions experiencesthe different range of Temperatures.So the Steel Structures are predominant thermalloading apart from mechanical loading at the interfaces of the different metallic components at severe environment conditions. Those structures must also be constructed to withstand thermal loads. In order to design the component, thermal loading must be converted to its equivalent mechanical stress. For that, an empirical model proposed for thermal equivalency to mechanical stress using a Finite Element analysis interfacial fracture mechanics technique. The study's major goal is to use material properties to assess the impact of these loads on bi material interfaces based on releasing rate of energy. By usage of FRANC 2D programmer, we suggested a simple model for Thermal equivalence to mechanical stress using the finite element approach.

Keywords: Franc 2D; Thermal Loading; Design Component; Thermal Equivalence;

Nomenclature

- α – Ratio of coefficient of expansion of material
- α_1 – coefficient of expansion of Structural Steel – IS 800: 2007 Code
- α_2 – coefficient of expansion of any Ferrous Material
- β – Ratio of Young's Moduli
- E_1 – Youngs Modulus of Structural Steel – IS 800: 2007 Code
- E_2 – Youngs Modulus of any Ferrous Material
- γ – Ratio of Poisions ratio
- υ_1 – Poisons ratio of Structural Steel – IS 800: 2007 Codeυ_2 – Poisons ratio of any Ferrous Material
- G– Energy Release Rate
- G_I – Rate of energy release – Mode I Failure
- G_{II}– Rate of energy release – Mode II Failure
- K– Stress Intensity Factor (SIF)

- K_I – Stress Intensity Factor – Mode I Failure
- K_{II} – Stress Intensity Factor – Mode II Failure
- σ–normal Stress
- T℃ – Change in Temperature in Degree Celsius
- FRANC 2D - FractureAnalysis Code 2D
- LEFM – Linear Elastic Fracture Mechanics

1. Introduction

According to elasticity theory, existence of square root singularity at the fracture tip under far field stress, and stress reaches to infinityat the crack tip.However, no material can withstand indefinite tension. Interfacial cracks in structural components are a common occurrence. Even though the interfacial crack is mode I loading, it is subjected to mixed conditions. At the interfacial crack tip, oscillatory singularity also prevails. As a result, the phenomena is explained using interfacial fracture mechanics. Linear Elastic Fracture Mechanics and Non-linear Fracture Mechanics are two branches of the fracture mechanics field. The current research is based on LEFM concepts. External loads, such as mechanical and thermal loads, are applied to structures.The analysis of structures subjected to thermal loading differs from the analysis of structures subjected to mechanical loading. Thermal loading causes stress induction in the component. As a result, a component that is subjected to thermal loading must be designed in terms of maximum stress/ maximum SIF, as well as material strength/fracture toughness. As a result, structures subjected to thermal loading can be constructed using mechanical stress/loading equivalents. Apart from mechanical loading, structural components in steel constructions made of cables, trusses, plates, and shells are subjected to major thermal loading. Those structures must also be constructed to withstand thermal loads. As previously stated, in order to design the component, thermal loading must be converted to its equivalent mechanical stress.

2. Objectives

- To evaluate the impact of thermal load on ratio of coefficient of expansion of material ($\alpha = \frac{\alpha_2}{\alpha_1}, 0.93 \leq \alpha \leq 1$),Ratio of Young's Moduli($\beta = \frac{E_1}{E_2}, 1 \leq \beta \leq 1.8$) and ratio ofpoison's ratio ($\gamma = \frac{\upsilon_2}{\upsilon_1}, 0.84 \leq \gamma \leq 1$) of an interfacial crack.
- To offer a simple paradigm for converting thermal load to mechanical load and vice versa using "thermal equivalence to mechanical stress".
- To see how the fracture parameters K_I& K_{II}, as well as G_I& G_{II}, affect the interfacial crack caused by thermal loading.

3. Methodology

For diverse material qualities, a plate with dimensions of 800mm x 300mm x 5mm and an interior interfacial fracture of 90mm was used.., $\alpha = \frac{\alpha_2}{\alpha_1}$ $(0.93 \leq \alpha \leq 1)$, $\beta = \frac{E_1}{E_2}$ $(1 \leq \beta \leq 1.8)$ and$\gamma = \frac{\upsilon_2}{\upsilon_1}$ $(0,84 \leq \gamma \leq 1)$ with an objective to establish relation between thermal load and mechanical loading is analyzed using Franc 2D.The material 1 confining the physical properties of structural steel as per IS 800:2007 Code. The load applied is within the proof stress of structural steel. The material 2 is chosen hypothetical values of ferrous materials like cost iron, mild steel etc. Endless In the following scenarios, element analysis is performed on a plate having an internal interfacial crack.

Material properties of an interfacial crack

$\alpha = 0.93$, $\beta = 1.8$ and $\gamma = 0.84$
Interfacial Crack with material properties
$\alpha = 0.95$, $\beta = 1.6$ and $\gamma = 0.87$
Interfacial Crack with material properties
$\alpha = 0.97$, $\beta = 1.4$ and $\gamma = 0.90$
Interfacial Crack with material properties
$\alpha = 0.98$, $\beta = 1.2$ and $\gamma = 0.93$
Interfacial Crack with material properties
$\alpha = 1.00$, $\beta = 1.00$ and $\gamma = 1.00$

A planar stress scenario is used to simulate the plate. The thermally loaded plate is investigated. For each temperature increment, the Stress Intensity Factors (SIF) G_I& G_{II} are noted. In addition, the same plate is exposed to mechanical loading. The finite element study yielded both the stress intensity factors (SIF) G_I& G_{II} for mechanical load increase. The global fracture parameter, energy release rate G (single parameter), is then calculated by adding all of the fracture parameters togetherG_I& $G_{II.}$

Then the relation between energy release rate (G),Normal Stress (σ^2), Ratio of Young'sModuli ($\beta = \frac{E_1}{E_2}$,$1 \leq \beta \leq 1.8$)and Ratio of Poison's ratio ($\gamma = \frac{\upsilon_2}{\upsilon_1}$, $0.84 \leq \gamma \leq 1$) developed as

$$G = f(\sigma^{n1}, \beta^{n2}, \gamma^{n3})$$

As it has been done in the case mechanical loading energy release rate G, Temperature (T℃) the ratio of coefficient of expansion ($\alpha = \frac{\alpha_2}{\alpha_1}$,$0.93 \leq \alpha \leq 1$) and ratio of Young's Moduli ($\beta = \frac{E_1}{E_2}$,$1 \leq \beta \leq 1.8$) and ratio of poison's ratio($\gamma = \frac{\upsilon_2}{\upsilon_1}$, $0.84 \leq \gamma \leq 1$) are correlated as

$$G = g(T^2, \alpha^{n4}, \beta^{n5}, \gamma^{n6})$$

Finally, as shown below, an empirical model for thermal equivalence to mechanical stress is derived from equations (1) and (2)

$$\sigma = \frac{2.732T\ \gamma^{0.90}\alpha^{0.585}}{\beta^{0.335}} \quad \text{-----------------------------} \quad (1)$$

The proposed empirical model is validated in this investigation, where $\alpha = \frac{\alpha_2}{\alpha_1}$, $\beta = \frac{E_1}{E_2}$and $\gamma = \frac{\upsilon_2}{\upsilon_1}$ FE The test is performed on a steel plate with dimensions of 800mm x 300mm x 5mm with a 90mm interfacial centered crack length (2a). All of the above-mentioned instances maintain the same boundary conditions and fracture length (90mm). In this study, the FractureAnalysis Code (FRANC 2D) software package was employed, which can extract stress intensity components and energy release rate. Carnell University in the United States developed the FRANC 2D. A planar stress scenario is used to simulate the plate. FRANC 2D is used to study a steel plate with an internal interfacial crack and varied material properties. Despite the fact that the plate's geometry and loading match to pure mode II, the crack is in a mixed mode due to its interface. It's also worth noting that the stress at crack tips reaches infinity. As a result, stress intensity parameters play a significant influence in the relationship between mechanical and thermal loads. As a result, finer mesh is used towards the fracture tip while coarser mesh is used distant from the crack. The plate that has been subjected to thermal loading is investigated. For each temperature increment, the total energy release rate (G) (which is calculated by adding GI&GII) is noted. In addition, the same plate is exposed to mechanical load. Finite element study yielded energy release rates (G) for mechanical load increment.

4. Results and Discussions

With the rising usage of computers and a focus on numerical approaches for engineering analysis, the finite element method was developed. Because many problems in fracture mechanics do not have closed form solutions, this method is extremely useful. Another significant benefit of finite element analysis is the simplicity with which models for practical instances may be built and analyzed by adjusting various parameters without the requirement for laboratory model tests. It is a well-known fact that FE Analysis can extract stress intensity components with a high degree of accuracy.

The finite element analysis of a bi-material interfacialcrack in a steel plate with various moduli of elasticity under uniform strain is described in this chapter. Finite Element analysis is performed on a steel plate with an interfacial fracture for various material characteristics ranging from α=0.93 to 1, β=1 to 1.8, and 0, γ =84 to 1 with the goal of establishing a relationship between thermal load (T^0C) and mechanical load (**τ**) by evaluating the following situations. Table 1 lists the various values of, and that were considered in this study.

Table: 1The various set of values of α, β and γ

Sr. No	$\alpha = \frac{\alpha_2}{\alpha_1}$	$\beta = \frac{E_1}{E_2}$	$\gamma = \frac{\upsilon_2}{\upsilon_1}$
1	0.93	1.8	0.84
2	0.95	1.6	0.87
3	0.97	1.4	0.9
4	0.98	1.2	0.93
5	1	1	1

4.1 Interior Interfacial Crack under Mechanical Loading

Normal stress was measured on a plate that had been subjected to mechanical loading. The Finite Element Analysis calculates the energy release rates (G) for each mechanical load increment.

The relationship between energy release rate and normal stress is exactly proportional to the data generated from FRANC2D for different material properties using multiple regression (G) (σ) Mechanical Stress As shown below, the elastic moduli ratio (β) ratio of poison ratio (γ) is established.

$$G = \frac{\sigma^2 \beta^{0.09}}{1288\ \gamma^{2.03}} \quad \text{-----------------------------} \quad (2)$$

Fig 1: *Deformation of the plate due to shear Stress (Mechanical Load)*

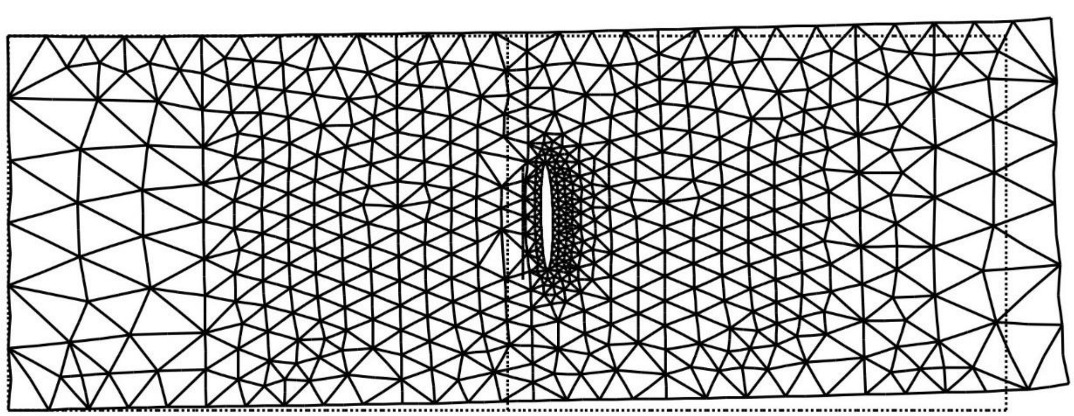
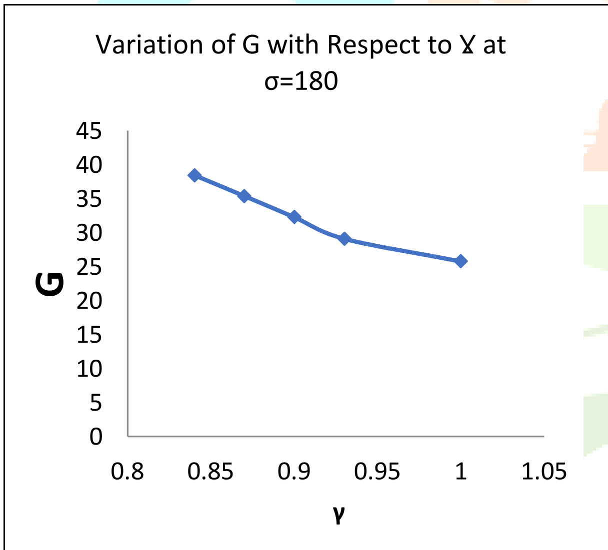
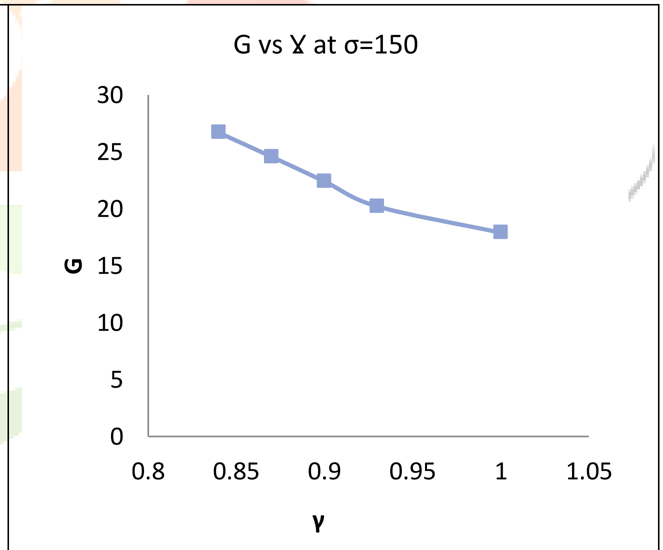


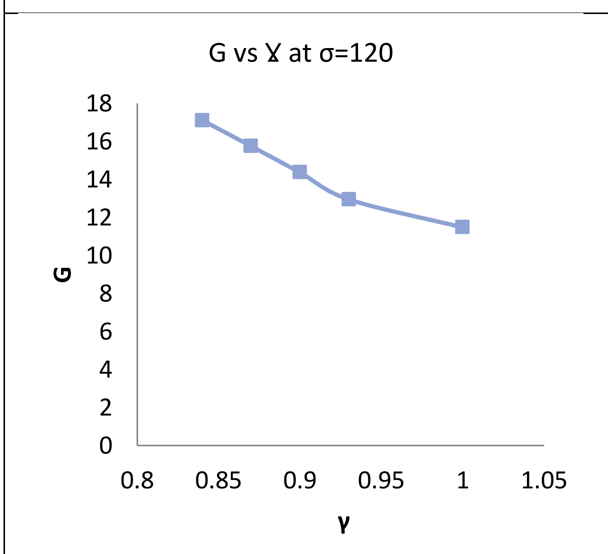
Table 2:Data generated from FRANC2D Mechanical Loading (normal stress)

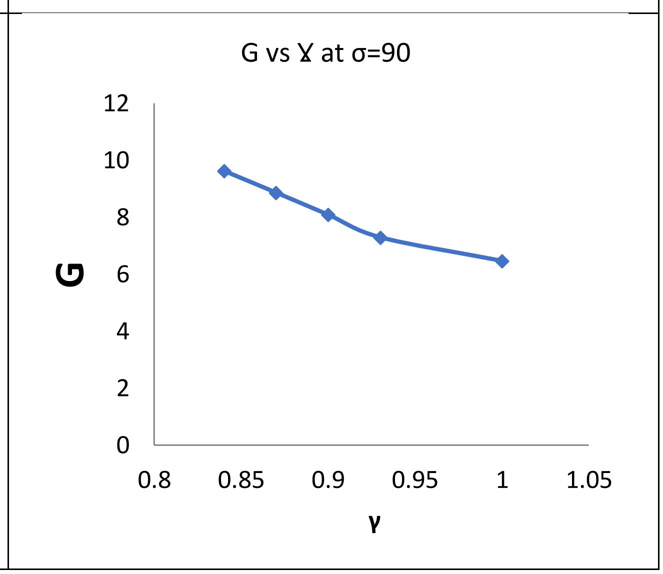
Sr. No	σ Stress (Mpa)	G_I (N/mm)	G_{II} (N/mm)	G (N/mm)	G total	σ^2	β	Γ
1	30	1.067	0.005	1.067	2.137	900	1.80	0.84
2	30	1.070	0.005	1.070		900	1.80	0.84
3	60	4.269	0.019	4.269	8.548	3600	1.80	0.84
4	60	4.279	0.019	4.279		3600	1.80	0.84
5	90	9.606	0.042	9.606	19.233	8100	1.80	0.84
6	90	9.627	0.043	9.627		8100	1.80	0.84
7	120	17.080	0.075	17.080	34.190	14400	1.80	0.84
8	120	17.110	0.076	17.110		14400	1.80	0.84
9	150	26.680	0.117	26.680	53.421	22500	1.80	0.84
10	150	26.740	0.118	26.740		22500	1.80	0.84
11	180	38.420	0.168	38.420	76.931	32400	1.80	0.84
12	180	38.510	0.170	38.510		32400	1.80	0.84
13	30	0.982	0.003	0.982	1.967	900	1.60	0.87
14	30	0.985	0.003	0.985		900	1.60	0.87
15	60	3.929	0.011	3.929	7.867	3600	1.60	0.87
16	60	3.938	0.012	3.938		3600	1.60	0.87
17	90	8.841	0.026	8.841	17.702	8100	1.60	0.87
18	90	8.861	0.026	8.861		8100	1.60	0.87
19	120	15.720	0.046	15.720	31.470	14400	1.60	0.87
20	120	15.750	0.047	15.750		14400	1.60	0.87
21	150	24.560	0.072	24.560	49.180	22500	1.60	0.87
22	150	24.620	0.073	24.620		22500	1.60	0.87
23	180	35.360	0.103	35.360	70.810	32400	1.60	0.87
24	180	35.450	0.105	35.450		32400	1.60	0.87
25	30	0.896	0.001	0.896	1.794	900	1.60	0.90
26	30	0.898	0.001	0.898		900	1.60	0.90
27	60	3.584	0.006	3.584	7.177	3600	1.60	0.90
28	60	3.593	0.006	3.593		3600	1.60	0.90
29	90	8.064	0.013	8.064	16.149	8100	1.60	0.90
30	90	8.085	0.013	8.085		8100	1.60	0.90
31	120	14.340	0.023	14.340	28.710	14400	1.60	0.90
32	120	14.370	0.024	14.370		14400	1.60	0.90
33	150	22.400	0.036	22.400	44.860	22500	1.60	0.90
34	150	22.460	0.037	22.460		22500	1.60	0.90
35	180	32.260	0.052	32.260	64.600	32400	1.60	0.90
36	180	32.340	0.053	32.340		32400	1.60	0.90
37	30	0.790	0.000	0.790	1.617	900	1.20	0.93
38	30	0.828	0.000	0.828		900	1.20	0.93
39	60	3.193	0.002	3.193	6.472	3600	1.20	0.93
40	60	3.279	0.002	3.279		3600	1.20	0.93
41	90	7.257	0.004	7.257	14.558	8100	1.20	0.93
42	90	7.301	0.004	7.301		8100	1.20	0.93
43	120	12.900	0.007	12.900	25.880	14400	1.20	0.93
44	120	12.980	0.007	12.980		14400	1.20	0.93

Sr. No	σ Stress (Mpa)	G_I (N/mm)	G_{II} (N/mm)	G (N/mm)	G total	σ^2	β	Γ
45	150	20.130	0.012	20.130		22500	1.20	0.93
46	150	20.320	0.011	20.320	40.450	22500	1.20	0.93
47	180	28.890	0.017	28.890		32400	1.20	0.93
48	180	29.360	0.016	29.360	58.250	32400	1.20	0.93
49	30	0.717	0.000	0.717		900	1.00	1.00
50	30	0.717	0.000	0.717	1.434	900	1.00	1.00
51	60	2.867	0.000	2.867		3600	1.00	1.00
52	60	2.867	0.000	2.867	5.734	3600	1.00	1.00
53	90	6.450	0.000	6.450		8100	1.00	1.00
54	90	6.452	0.000	6.452	12.902	8100	1.00	1.00
55	120	11.470	0.000	11.470		14400	1.00	1.00
56	120	11.470	0.000	11.470	22.940	14400	1.00	1.00
57	150	17.880	0.000	17.880		22500	1.00	1.00
58	150	17.960	0.000	17.960	35.840	22500	1.00	1.00
59	180	25.760	0.000	25.760		32400	1.00	1.00
60	180	25.850	0.000	25.850	51.610	32400	1.00	1.00









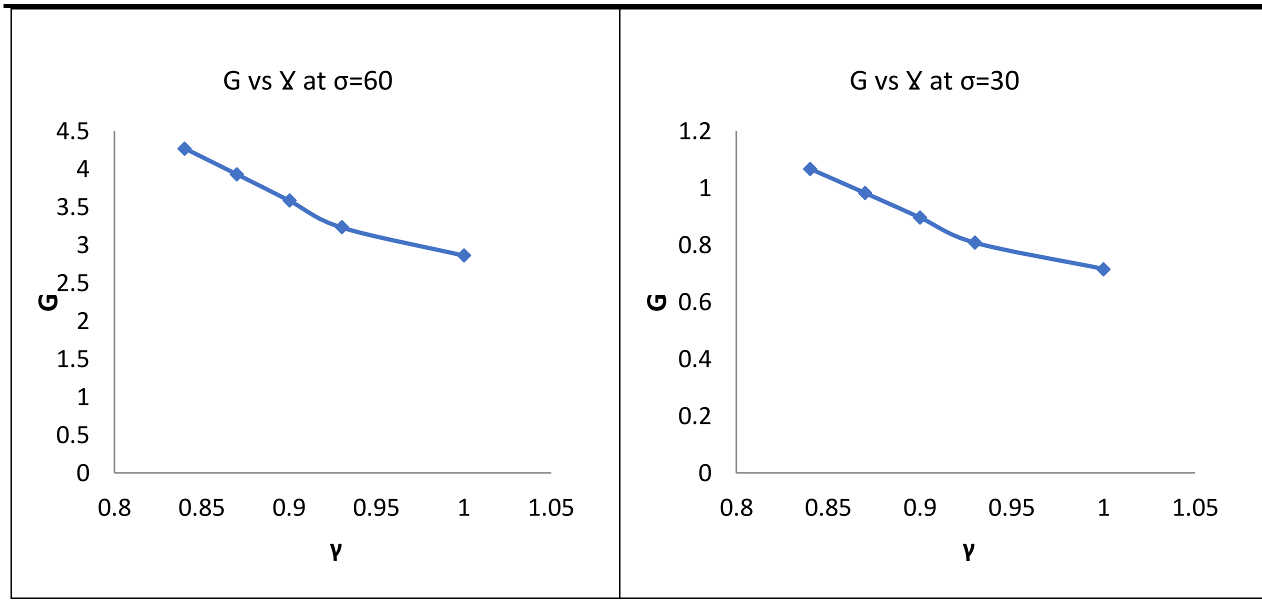
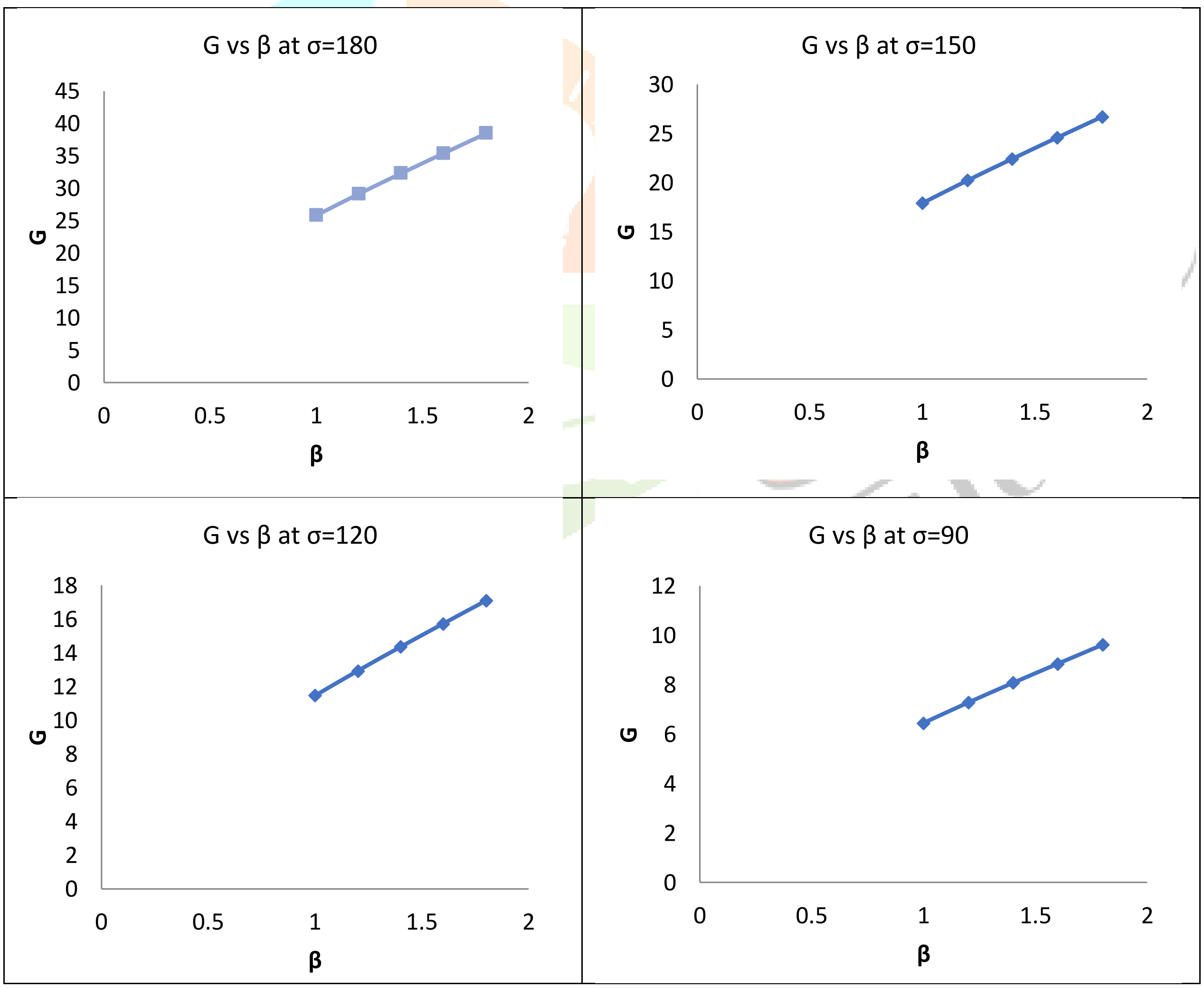


Fig 2. Variation of G with respect to γwith variations of σ



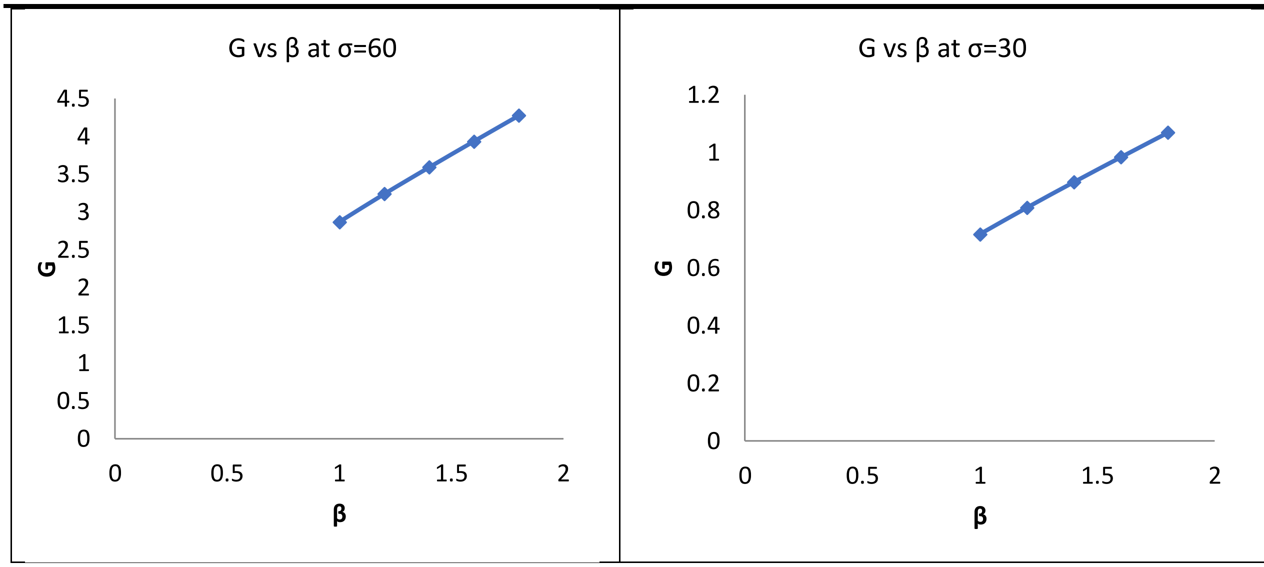


Fig 3. Variation of G with respect to βwith variations of σ

4.2 Interior Interfacial Crack Under Thermal Loading

The interfacial crack in a steel plate that has been subjected to heat loading is investigated. The Finite Element Analysis calculates the energy release rates (G) for each temperature increment. Multiple regressions of the data (Table3) from FRANC2D for different material properties establish the association between energy release rate (G), temperature (TC), ratio of coefficient of expansion (α), elastic moduli ratio (β), and ratio of Poisson's ratios (γ). As with mechanical loading, it is assumed that the energy release rate due to thermal load is connected with, and. The connection is strong.

$$G = \frac{T^2 \alpha^{1.17}}{229\,\beta^{0.58}\gamma^{0.23}} \quad \text{---------------------------} \quad (3)$$

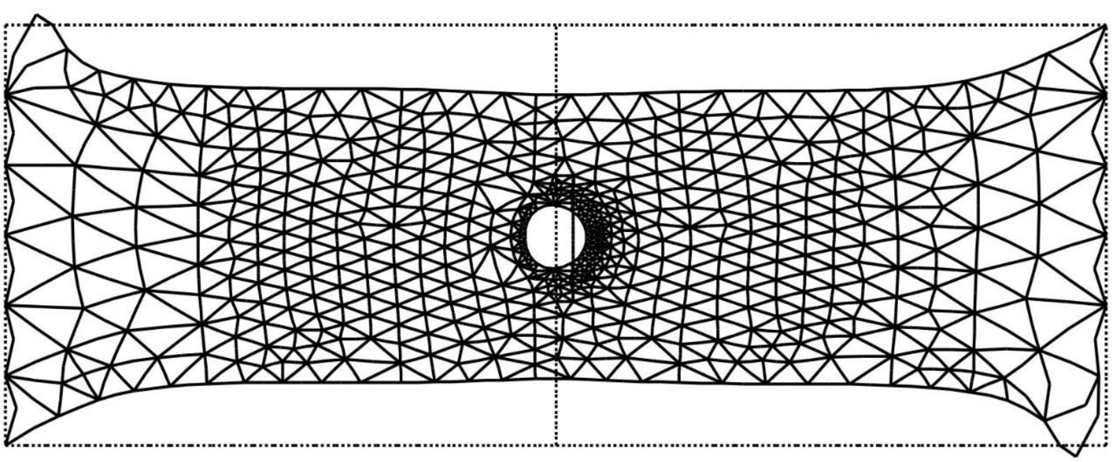


Fig 4: Deformation of the plate due to Thermal Stress (Thermal Load)

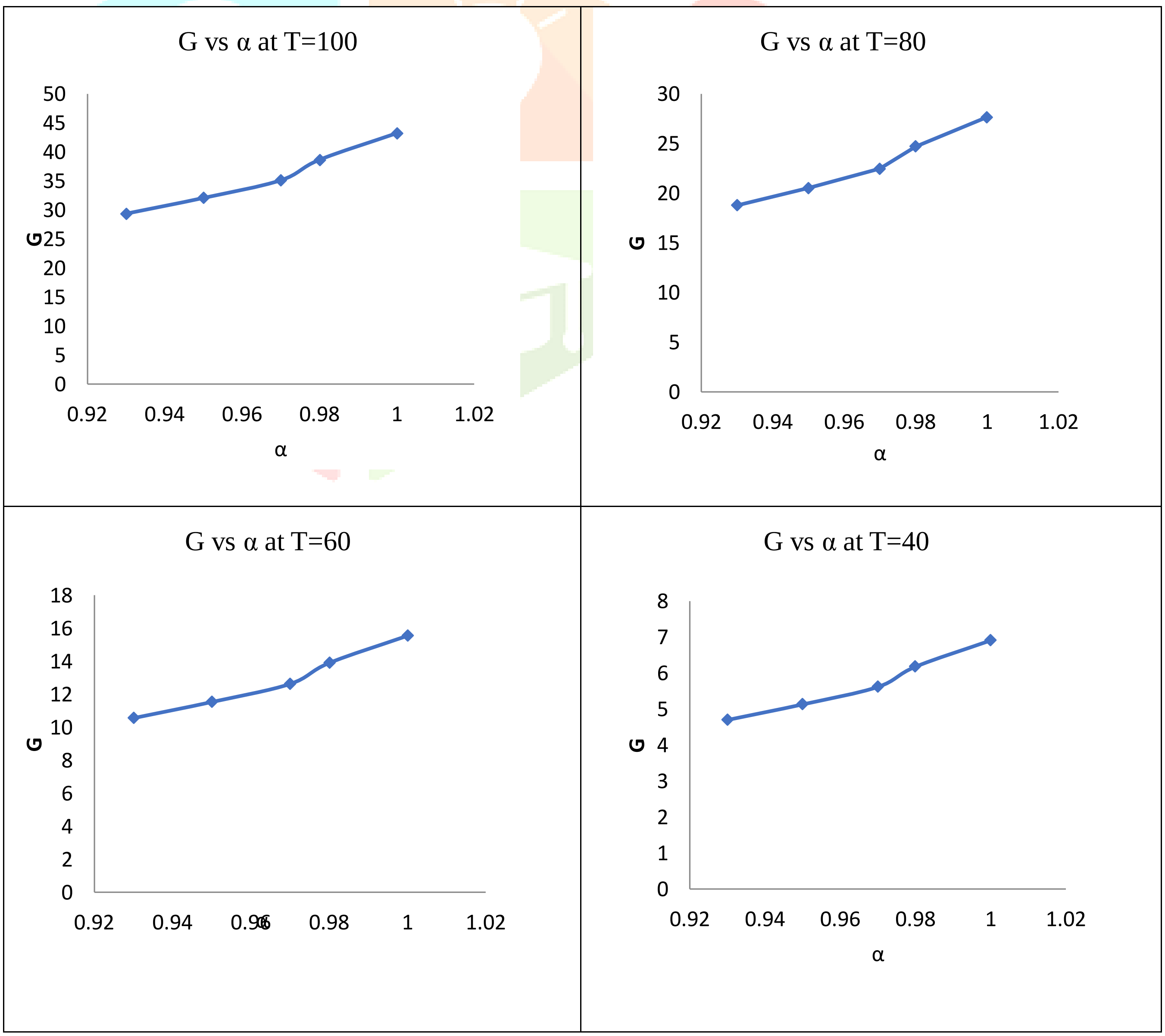
Table 3: Data generated from FRANC2D Thermal Loading

Sr. No	T℃	G_I (N/mm)	G_{II} (N/mm)	G (N/mm)	G total	α	β	Γ
1	20	1.17	0.01	1.170		0.93	1.80	0.84
2	20	1.18	0.00	1.179	2.349	0.93	1.80	0.84
3	40	4.68	0.03	4.678		0.93	1.80	0.84
4	40	4.72	0.01	4.716	9.394	0.93	1.80	0.84
5	60	10.53	0.06	10.530		0.93	1.80	0.84
6	60	10.61	0.03	10.610	21.140	0.93	1.80	0.84
7	80	18.71	0.11	18.710		0.93	1.80	0.84
8	80	18.86	0.05	18.860	37.570	0.93	1.80	0.84
9	100	29.24	0.18	29.241		0.93	1.80	0.84
10	100	29.48	0.07	29.480	58.721	0.93	1.80	0.84
11	20	1.28	0.01	1.278		0.95	1.60	0.87
12	20	1.29	0.00	1.287	2.565	0.95	1.60	0.87
13	40	5.11	0.02	5.112		0.95	1.60	0.87
14	40	5.15	0.01	5.149	10.261	0.95	1.60	0.87
15	60	11.50	0.05	11.500		0.95	1.60	0.87
16	60	11.59	0.02	11.590	23.090	0.95	1.60	0.87
17	80	20.45	0.09	20.450		0.95	1.60	0.87
18	80	20.60	0.03	20.600	41.050	0.95	1.60	0.87
19	100	31.95	0.14	31.950		0.95	1.60	0.87
20	100	32.18	0.05	32.180	64.130	0.95	1.60	0.87
21	20	1.40	0.00	1.399		0.97	1.40	0.90
22	20	1.41	0.00	1.409	2.808	0.97	1.40	0.90
23	40	5.60	0.02	5.596		0.97	1.40	0.90
24	40	5.64	0.00	5.637	11.233	0.97	1.40	0.90
25	60	12.59	0.04	12.590		0.97	1.40	0.90
26	60	12.68	0.01	12.680	25.270	0.97	1.40	0.90
27	80	22.38	0.06	22.380		0.97	1.40	0.90
28	80	22.55	0.02	22.550	44.930	0.97	1.40	0.90
29	100	34.97	0.10	34.970		0.97	1.40	0.90
30	100	35.23	0.02	35.230	70.200	0.97	1.40	0.90
31	20	1.54	0.00	1.537		0.98	1.20	0.93
32	20	1.55	0.00	1.553	3.090	0.98	1.20	0.93
33	40	6.15	0.01	6.147		0.98	1.20	0.93
34	40	6.21	0.00	6.212	12.359	0.98	1.20	0.93
35	60	13.83	0.02	13.830		0.98	1.20	0.93
36	60	13.98	0.00	13.980	27.810	0.98	1.20	0.93
37	80	24.59	0.04	24.590		0.98	1.20	0.93
38	80	24.85	0.00	24.850	49.440	0.98	1.20	0.93
39	100	38.42	0.05	38.420		0.98	1.20	0.93
40	100	38.82	0.00	38.820	77.240	0.98	1.20	0.93
41	20	1.73	0.00	1.725		1.00	1.00	1.00
42	20	1.73	0.00	1.731	3.456	1.00	1.00	1.00
43	40	6.90	0.00	6.899		1.00	1.00	1.00
44	40	6.92	0.00	6.924	13.823	1.00	1.00	1.00

Sr. No	T ℃	G_I (N/mm)	G_{II} (N/mm)	G (N/mm)	G total	α	β	Γ
45	60	15.52	0.00	15.520		1.00	1.00	1.00
46	60	15.58	0.00	15.580	31.100	1.00	1.00	1.00
47	80	27.60	0.00	27.600		1.00	1.00	1.00
48	80	27.69	0.00	27.690	55.290	1.00	1.00	1.00
49	100	43.12	0.01	43.120		1.00	1.00	1.00
50	100	43.27	0.00	43.270	86.390	1.00	1.00	1.00

Solving the equations 1 & 2 by eliminating G the equivalents between the Thermal load and Mechanical Stress is established in terms of α, β and γ as given below.

$$\sigma = \frac{2.372 \ T \alpha^{0.585} \gamma^{0.90}}{\beta^{0.335}} \quad \text{----------------------------} \quad (4)$$



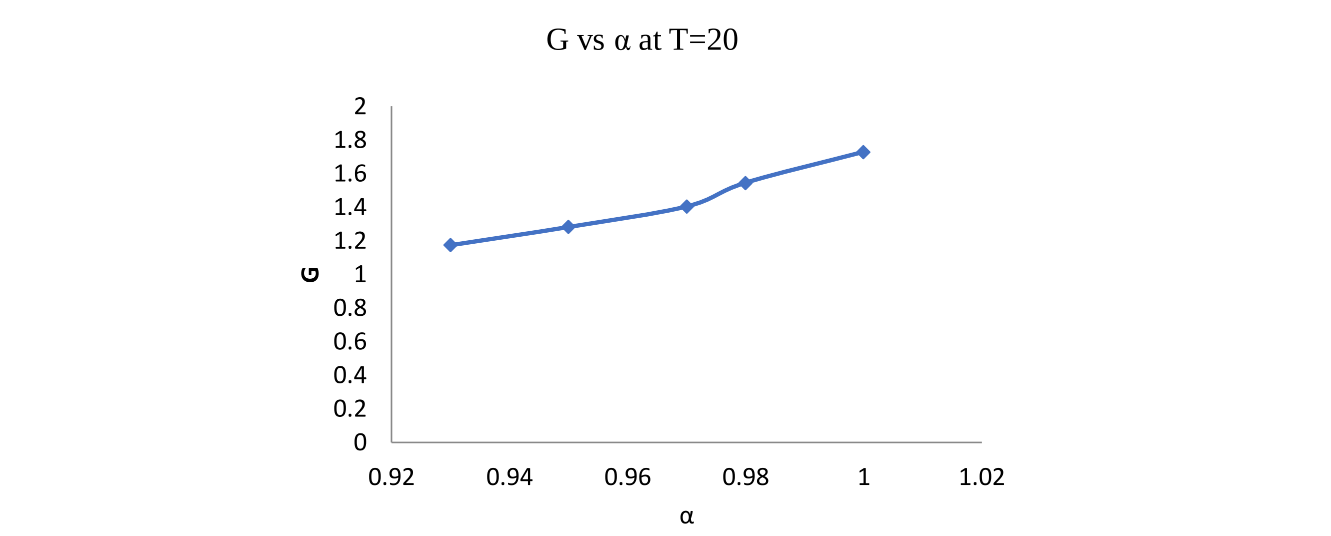


Fig 5: Variation of G with respect to α with variations of T

5. Conclusion and Discussion

It is impossible to establish a straight equivalency between mechanical and thermal loads. As a result, it is assumed that it can be done using the fracture mechanicsapproachenergyreleaserate (G) is related to temperature (TC), Mechanical Stress (σ) ratio of coefficient of expansion (α), elastic moduli ratio (β), and ratio of Poisson's ratio (γ) separately (Eq 1 & 2) using interfacial fracture mechanics and FE analysis. Then, in terms of the, and, temperature (T^0C) and mechanical stress (σ) are connected α, βand γ(Eq 3). According to the FE analysis of the interfacial fracture, the interfacial crack experiences a mixed scenario for both mechanical and thermal loads. This is owing to the material properties on both sides of the interface being different.It is also observed that in the mechanical analysis that$K_{II}$is greater than $K_I$and in Thermal analysis K_I is greater than K_{II}.

5.1 Limitations of the Empirical model

Any theory or model, no matter how accurate or sophisticated, is guaranteed to have some limits. That is, the model can be used within the limitations of the domain. The proposed model is no different. The following limitations apply to the current model.

- The proposed model is applicable to linear elasticmaterials with ratio of coefficient of expansion ($\alpha = \frac{\alpha_2}{\alpha_1}$, $0.93 \leq \alpha \leq 1$) and ratio of Youngs Moduli ($\beta = \frac{E_1}{E_2}$, $1 \leq \beta \leq 1.8$) and ratio of poison's ratio ($\gamma = \frac{\upsilon_2}{\upsilon_1}$, $0.84 \leq \gamma \leq 1$)
- The proposed model is applicable for plane stress problems
- Even though material properties fixed,the combined effect of two different materials at their interfaces is innovative simulation work on franc 2d and it is related to normal stress which acts normal to crack face
- The value ofα is the ratio ofcoefficient of expansion of the material which affects the direct strain of the material in thermal analysis.

- The range of temperature drop or rise is chosen normal atmospheric standards 0 to100 degree Celsius without altering the physical properties of the material and fit the temperature range to simulate the franc2d problem.

5.2 Validation of the Proposed Model

The suggested empirical model is validated using FE analysis on steel plates of various sizes.800x300x5 mm with 90mm interior interfacialcrackwithα = 0.96 β = 1.3 and γ = 0.95. Energy release rate (G_I&G_{II}) are noted for Temperature drop 40 degrees centigrade in natural environment, and then equivalent mechanical stress correspondent to temperature drop of 40 degree centigradeis calculated using the model shown in Eq 3. FRANC 2D is used to examine a plate with dimensions of 800x300x5 mm and a 90mm internal interfacial crack subjected to the computed equivalent mechanical force. As shown in Table 4, the energy release rates (G_I&G_{II}) are observed and compared to those obtained from thermal loading.

Table 4: Validation of the proposed empirical model – "Thermal Equivalenceto Mechanical stress"From the above discussions the following conclusions are drawn

Crack Tip	Thermal Load - -50 C			Mechanical Load -130 Mpa			Error
	G_I	G_{II}	G_{Temp}	G_I	G_{II}	G_{Mech}	$\frac{(GTemp - GMech)}{GTemp}$ x 100
1	5.761	0.009	5.761	6.037	0.007	6.037	- 7.35 %
2	5.819	0.003	5.819	6.394	0.007	6.394	
	G_{Total}		11.580	G_{Total}		12.431	

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