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Computational Analysis of Predicting Stress Intensity Factor Using Hdmr Technique



Abstract: - The present research focused to develop meta-model (MM) as a low-cost substitute for the Finite Element Method (FEM), to forecast the Stress Intensity Factor (SIF) of a semi-elliptic crack propagating. Multi-linear regression (MLR) based MM is developed for predicting the crack propagation. Three parameters—Root Mean Square Error (RMSE), Maximum Absolute Error (AAE), and Average Absolute Error—are examined to compare the MM's precision (AAE).

Keywords: Meta Model, Stress Intensity Factor, Semi-elliptic crack, Finite Element Method and Multi Linear Regression.

: INTRODUCTION

Meta-models (MMs) are data-driven models that use a small number of computationally expensive simulations (CES) to try and forecast the complex input/output (I/O) characteristics of a supporting system (Arvind et. al., 2017). Fig. 1 displays a schematic that shows how to manufacture MMs using SUMO. It is important to distinguish MMs from the less reliable CES, which is a simplified form. Instead, MMs accurately mimic the behavior of the CES while having a cheap computing cost. Since the analyst's goal is to accurately establish the I/O relationship, Understanding the mechanics of the MM's code is not required., which is another intriguing property of the MMs (Renhe et. al., 2021).

Thus far, parametric research, design automation, optimization, MMs have been used in sensitivity analysis, design space exploration, and other processes. (Saman et. al., 2012). MMs are commonly used to simulate the output of a single, expensive simulation algorithm that must be run numerous times to produce results that are suitable for every application. In this study, MMs are employed to forecast a propagating crack's stress intensity factor (SIF). In order to forecast the SIF in metallic structures, the evaluation of fatigue life in the offshore sector, which is based on the widely used standards Finite Element Methods (FEM) or closed form solutions are used in BS-7910 and DNVGL-RP-C210. The primary objective of this study is to evaluate the appropriateness of several MMs for predicting the SIF of a semi-elliptic fracture in an offshore environment.

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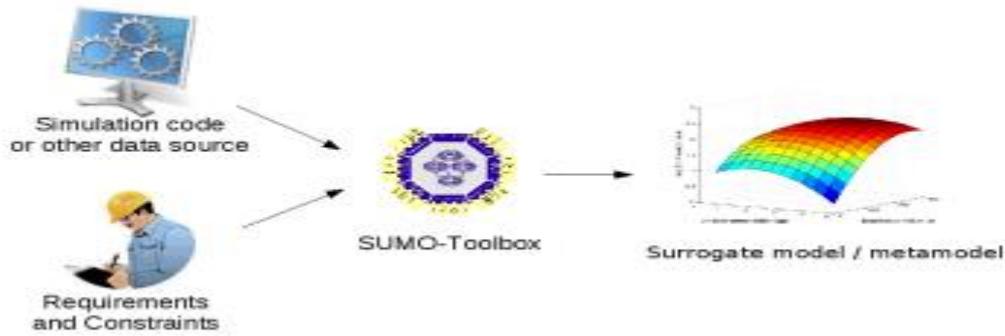


Figure 1 Schematic showing creation of MMs

The LHS design function is implemented by randomly generating several groups of sample points and selecting the groups with the best space filling ability. This demonstrates that the random sample points produced by the optimal design methods of the Latin hypercube can fill the design space uniformly. Reliability analysis has often employed the active learning method surrogate model because it offers a good trade-off between efficiency and accuracy (Hong et. al., 2022). In last one decade, a range of various methods for dependability analysis, including analytical, sampling, and MM-based approaches, have been planned. MM are at the heart of this discipline, since most of the constituent artifacts and mechanism are based on them, including models and transformations.

1. FACTOR OF STRESS INTENSITY

The condition of the fracture tip's stress field is determined by the stress intensity factor (SIF) (Sadesh et. Al., 1979). George R. Irwin first used the term SIF in 1957 to explain the fracture front's stress field. The main component of SIF was Westergaard's solution (Eq. 1), which used the Airy stress function to describe the local stress field near the fracture front. The Westergaard's remedy is expressed as

$$K_I = \sigma_0 Y \sqrt{\pi a} \tag{1}$$

The crack depth is represented by "a" in the equation above, and the notional When it looks in the plate without the break, a uniform stress field is represented by Y.G. Irwin discovered in 1957 that a scaling factor known as the stress intensity factor might be used to represent the stresses surrounding a crack. He proved that there are three different kinds of cracking modes that are linearly independent that may be identified in a crack that is exposed to any random loading. These loads can be classified as Mode I, Mode II, or Mode III. In engineering design, mode I loads are the most prevalent kind that are encountered. The crack opening mode is subject to the SIF for mode-I, which is known as K_I .

2.1 MANY LINEAR REGRESSIONS

One statistical method called multiple linear regression (MLR) utilizes some descriptive variables to forecast a response variable's outcome. Based on the regression equation, a basic linear regression demonstrates how the independent variable (x) and the dependent variable (y) are related. On the other hand, the plane that best fits the data is found using the MLR model, for instance with two independent variables. For MLR analysis, the regression coefficients in Eq. (2) are estimated using the least squares method. Each independent variable's unconnected contributions are shown by the regression coefficients.

$$\hat{y} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_n x_n + \epsilon \tag{2}$$

Where, for $i=no.$ of observations: y_i =dependent variable; x_i =explanatory variables; β_0 =y-intercept; β_n =slope coefficients for each explanatory variable; ϵ =the model's error term. The computations used in finding the regression coefficients, sum of squares for residuals, regression sums, etc. are rather complex (Yu et. al., 2022). The calculation is often done in a matrix form as shown below:

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ \vdots \\ y_n \end{bmatrix} = \begin{bmatrix} 1 & x_1 & x_1^2 & \dots & x_1^m \\ 1 & x_2 & x_2^2 & \dots & x_2^m \\ 1 & x_3 & x_3^2 & \dots & x_3^m \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & x_n & x_n^2 & \dots & x_n^m \end{bmatrix} \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \vdots \\ \beta_m \end{bmatrix} + \begin{bmatrix} \varepsilon_0 \\ \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{bmatrix} \tag{3}$$

This is due to the high amount of data and correlation among each data type.

3.FINITE ELEMENT MODELLING

ANSYS is a commercial software used to generate a finite element model (FEM). The research has employed two distinct mesh sizes, whereby the crack location's surrounding mesh—that is, the areas at the crack front and surrounding areas— is more sophisticated than the geometry of the other plates. In order to avoid convergence problems and obtain a more accurate SIF solution, a finer mesh is used at the fracture position (Jakeman et. al., 2022). The rectangular plate is subjected to a uniaxial tensile force on its smaller sides. A central fatigue fracture in a mode 1 opening is the damage that is being examined; Its length is orthogonal to the axis of loading.. "a" stands for the depth of the fracture, and "2c" for the length of the crack. The data (load, a, and c combined) produced using Latin Hypercube Sampling (LHS) is used to run the FEM. The range of the analysis's load (L) is between 100 and 200 MPa, and the range of the crack depth (a) is between 1 and 8 mm. Similarly, the half crack length (c) ranges from 2 mm to 22 mm. Table 1 displays the material parameters of the chosen specimen.

3.2 PROCEDURE TO GENERATE A MODEL USING ANSYS

A mesh is made up of elements which contain nodes that represent the shape of the geometry. A geometry or CAD model is generated using different mesh sizes and the corresponding figure is shown in Fig. 2

Step-1 Open ANSYS Workbench

Step-2 ANSYS Workbench open in left side some contents will show

Step-3 In that content click the static structural option

Step-4 After selecting static structural option small window will pop up in middle in that window shown in Fig. 3

Step-5 In that window click the geometry option design modeller page will opening

Step-6 In the design modeller page left side small window pop up and that window three option will pop up as illustrated in Fig 4

Step-7 In that option will select XY plane after selecting plane go to draw option and select a rectangular shape draw the rectangular shape and set the dimensions (length = 273 mm and width = 63 mm)

Step-8 After give the dimensions selection extrude option and give the thickness of that model next will generate that model new model window will be popup

Table 1 API5L-Grade B's material and geometric qualities

Material Characteristics	Worth	Properties of Geometry	Value
Elasticity Modulus	210 GPa	Length	273 mm
Poisson Ratio	0.3	Width	60 mm
Yield Stress/Tensile Stress	241 GPa/350 GPa	Thickness	10 mm

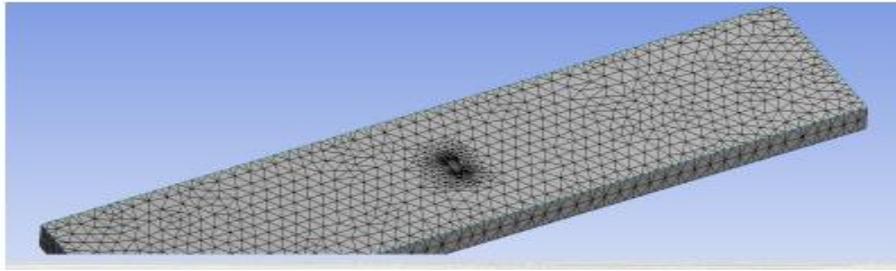


Figure 2FEM model of plate and crack geometry

Step-9 In new model page will open in that page left side small window will pop up

Step-10 In that window will select first coordinate geometry set the geometry part in the middle of that model.

Step-11 Next will select the mesh option to set the mesh size and mesh shape then generate the model

Step-12 In next go to plane option insert the fracture option in that fracture option insert the semi elliptical crack option

Step-13 After selecting the crack option give the crack dimensions (like as length&and depth)

Step-14 In next will click the static structural option and give edge supports one edge will give fixed support another end tensile load is shown Fig 5

Step-15 After completing loading given go to solution option

Step-16 Add the solution information, total deformation, equivalent elastic strain and also fracture tools (SIF values K_1, K_2, K_3)

Step-17 After total adding will give the load and crack length and crack width value *Generate* option will click

Step-18 SIF value will pop up in the left side of model red colour indicates maximum SIF value blue colour indicates minimum SIF value is shown in results chapter

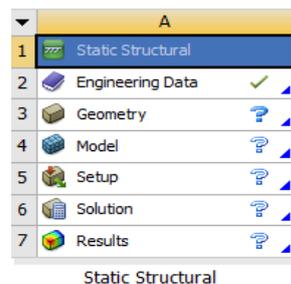


Figure 3 Static structural window in the ansys software

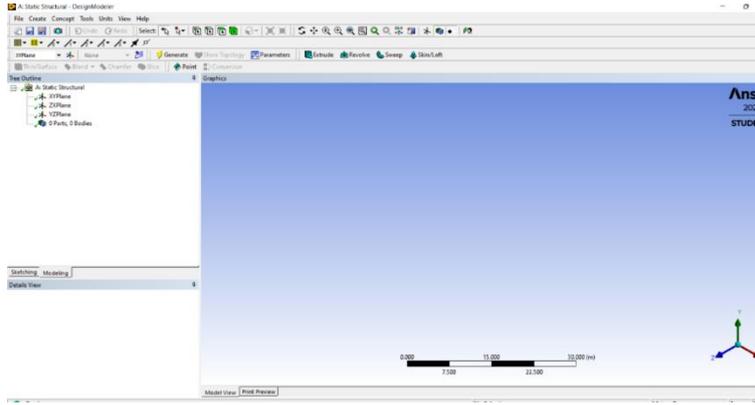


Figure 4 Design modeller page in Ansys

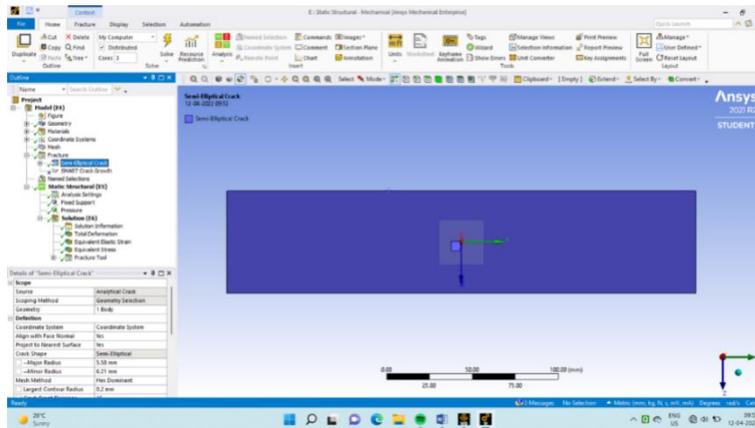


Figure 5 All values adding Ansys software with model image

3.3 GENERATION OF META-MODELS

Table 2 displays the thirty distinct combinations of loading levels and crack sizes that were produced using MATLAB software. In the MATLAB,LHS technic-based data points are generated by following the given code.

$$X=lhsdesign(30,3);L=X(:,1)*100+100;a=X(:,2)*7+1;c=X(:,3)*20+2;[L a c]$$

Table 2 Data points coming from the MATLAB

Load (Mpa)	Crack Depth Measured in mm (a)	Length of Half Crack in Millimeters
100.28	7.61	18.30
159.99	7.37	10.23
191.79	6.91	03.63
178.58	2.64	06.85
115.13	5.15	04.31
137.43	1.06	07.33
152.25	4.21	11.18
194.05	3.07	13.26
111.76	2.25	11.92
189.88	2.52	20.62
176.08	3.92	12.39
140.92	1.77	21.04
118.42	5.25	14.422

149.49	4.41	21.49
155.52	6.21	05.58
107.97	6.50	16.81
169.36	5.70	08.04
120.87	1.27	15.35
145.85	1.64	17.87
160.27	3.19	03.24
125.76	4.59	06.20
130.78	6.00	05.27
172.70	3.59	14.98
129.04	7.23	19.64
186.36	6.75	08.75
198.07	7.97	19.01
181.13	4.74	16.40
134.84	3.41	02.21
165.24	2.05	13.50
104.51	5.51	09.65

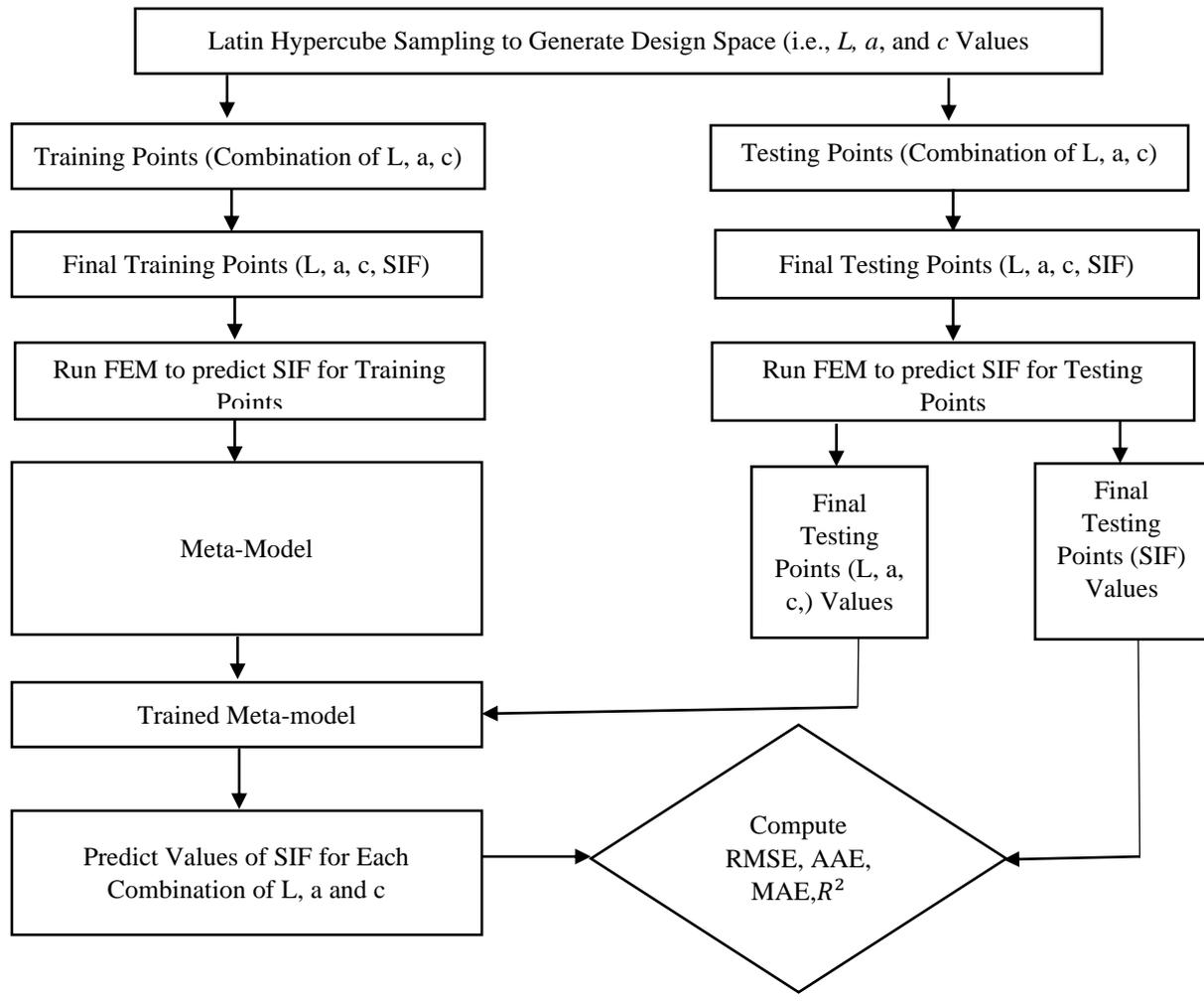


Figure 6 MM construction flowchart for SIF prediction

The SIF was determined by finite element analysis, and an MM is built to predict its value using the flowchart displayed in Figure 6. After that, thirty values of the SIF produced by FEM were utilized to train each MM

independently. For example, Equations (5) and (6) provide the MLR and PR equations, which were created by fitting them to the training set.

$$\text{SIF Prediction} = -445.36 + 3.85 L + 31.55 a + 32.65 c \quad (5)$$

$$\text{SIF Prediction} = -4.84 e^{-4}(L * L) + 2.01 e^{-1}(L * a) + 2.13 e^{-1}(L * c) + 3.58 (a * a) - 1.84 (a * c) + 8.8e^{-1}(c * c) \quad (9) + 1.08 (L) - 3.65 (a) - 12.94 (c) + 38.67 \quad (6)$$

As demonstrated, the variables. For loading, crack depth, and half crack length, respectively, L, a, and c stand., respectively, in Equations (11) and (12). After the MM has been trained, it must be tested by contrasting its predicted values with the SIF values that were obtained from ANSYS.

4.RESULTS AND DISCUSSION

For the thirty combinations (load, crack length and crack width give in the Table 2), SIF(*K_I*) values are computed from the formula, ANSYS, and MMs are shown in Table 3.FEA based results are depicted in Fig. 7 and Fig. 8. Plotting the SIF values acquired by the different approaches results in Figure 4.3. The error is calculated using Eqs. (7) and (8) and is shown in Table 4.

Table 3 SIF using 30 test points BS7910, ANSYS & MLR

S.NO.	Loading (MPa)	Crack Depth in mm(a)	Half Crack Length in mm (c)	SIF(K) (MPa-√mm)	ANSYS (MPa-√mm)	MLR (MPa-√mm)
1	100.28	7.61	18.30	605.39	600.96	778.30
2	159.99	7.37	10.23	731.16	732.55	737.13
3	191.79	6.91	03.63	786.16	622.34	629.56
4	178.58	2.64	06.85	537.29	508.01	549.11
5	115.13	5.15	04.31	476.40	355.97	301.09
6	137.43	1.06	07.33	280.81	270.81	356.51
7	152.25	4.21	11.18	533.07	596.53	638.65
8	194.05	3.07	13.26	688.04	688.62	831.53
9	111.76	2.25	11.92	300.62	331.35	445.09
10	189.88	2.52	20.62	619.05	655.16	1038.42
11	176.08	3.92	12.39	647.40	617.82	760.75
12	140.92	1.77	21.04	537.86	383.07	839.98
13	118.42	5.25	14.42	495.13	558.74	647.07
14	149.49	4.41	21.49	743.19	756.03	970.96
15	155.52	6.21	05.58	590.94	556.54	531.50
16	107.97	6.50	16.81	501.43	588.06	724.24
17	169.36	5.70	8.04	578.99	606.13	649.01
18	120.87	1.27	15.35	285.95	267.34	561.23
19	145.85	1.64	17.87	271.89	378.29	751.36
20	160.27	3.19	03.24	402.74	378.75	378.11
21	125.76	4.59	06.20	544.65	379.49	386.06
22	130.78	6.00	05.27	635.76	446.39	419.50
23	172.70	3.59	14.98	676.02	677.00	821.89
24	129.04	7.23	19.64	707.61	851.84	920.79
25	186.36	6.75	08.75	961.52	766.21	770.77
26	198.07	7.97	19.01	1132.45	1054.2	1189.33
27	181.13	4.74	16.40	794.93	770.25	936.99
28	134.84	3.41	02.21	400.63	304.76	253.51
29	165.24	2.05	13.50	410.22	451.47	696.26
30	104.51	5.51	09.65	550.64	407.82	445.91

Table 4 Comparisons of various meta-models

	RMSE	AAE	MAE
MLR	171.17	111.49	97.60
SIF	93.50	27.24	14.02

Four metrics—Root Mean Square Error (RMSE), Average Absolute Error (AAE), Maximum Absolute Error (MAE), and coefficient-of-determination (R!)—are used to assess the correctness of the MMs. In terms of math, these are written as:

$$RMSE = \sqrt{\sum_{i=1}^n (Y_i - y_i)^2} \tag{7}$$

$$AAE = \frac{\sum_{i=1}^n |Y_i - y_i|}{n} \tag{8}$$

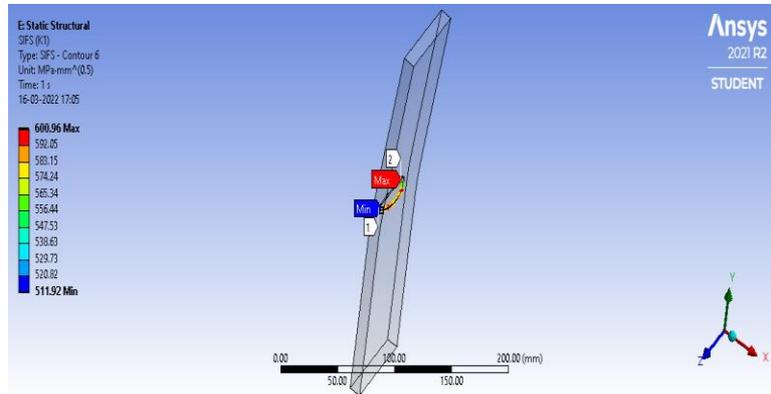


Figure 7 SIF for sample 1st test point using ANSYS

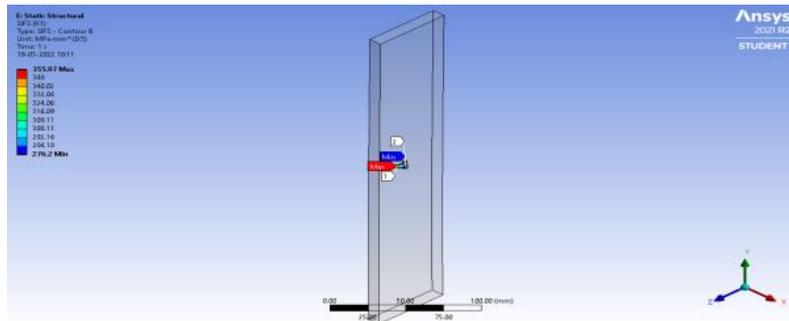


Figure 8 SIF for sample 5th test point using ANSYS

All four accuracy measurement measures are based on the fundamental comparison of prediction values using the sincere reply, in this in the event that the SIF value determined by FEM.

5. CONCLUSION

This paper proposes novel empirical SIF equations for a semi-elliptical surface's SIF fracture within a flat plate's limited width and thickness, which are innovative and derived from mathematical judgment. These formulas can be used for relative crack depths of less than 0.8 and crack aspect ratios between 0.2 and 1.0. By contrasting with experimental results under tension and bending loading, it was demonstrated. It should be possible to forecast the fatigue lifetimes of joints using the new SIF equations. We investigated the main causes of the SIF's decreased

accuracy derived from an empirical formula. The analytical SIF formula was then used to modify the necessary correction factors in this formula. Regarding the decline of one significant the corrected formula's adjustment factor, the finite element simulation was used. The suggested modified formula for calculating the SIF of a semi-elliptical surface fracture in joints that are bent was found to be accurate and dependable.

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