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Damping Mechanism in Welded Structures

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***Abstract*—Response surface methodology with Box–Benhken (BB) design of experiment approach has been utilized to study the mechanism of interface slip damping in layered and jointed tack welded beams with varying surface roughness. The design utilizes the initial amplitude of excitation, tack length and surface roughness at the interfaces to develop the model for the logarithmic damping decrement of the layered and jointed welded structures. Statistically designed experiments have been performed to estimate the coefficients in the mathematical model, predict the response, and check the adequacy of the model. Comparison of predicted and experimental response values outside the design conditions have shown good correspondence, implying that empirical model derived from response surface approach can be effectively used to describe the mechanism of interface slip damping in layered and jointed tack welded structures.

***Keywords*—Interface slip damping, welded joint, surface roughness, amplitude, tack length, response surface methodology.

I. Introduction

OVER the years, researchers have emphasized their studies on the development of mathematical models for the mechanism of damping and techniques to improve the damping capacity of laminated structures to control the adverse effects of vibrations. Following the requirements of modern technology, there has been significant increase in demand to design, develop and fabricate machine tools, space structures, high speed automobiles, etc. to meet the global demand. The manufacture of such structures also requires high damping capacity and stiffness with light weight for its effective use. Such requirements necessitated and popularized the use of welded, bolted and riveted layered beams as structural members with high damping capacity. In the alternative, cast structures can be used, but unfortunately, these are more expensive to manufacture and as a result, the deployment of welded, bolted and riveted multi-layered beam structures is becoming increasingly common in such industries.

Joints which contribute significantly to the inherent damping are present in most of the fabricated structures. Joints have a great potential for reducing the vibration levels of a structure and have attracted the interest of many researchers.

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The earlier workers such as; [1]-[5] have presented different techniques of improving the damping capacity of layered and jointed bolted structures without considering the effects of surface irregularities and asperities.

Many comprehensive review papers on joints and fasteners have appeared in recent years. Berger [6] has studied the effect of microslip on the passive damping of a jointed structure. Csaba [7] proposed a microslip friction mechanism with a quadratic normal load distribution based on the model developed by [8] where the shear layer has been neglected for simplicity. Berger et al. [9] have formulated a new model based on microslip approach for accurate determination of system dynamic response under a variety of contact conditions.

Although a lot of work has been carried out on the damping capacity of bolted structures, but a little amount of work has been reported till date on the mechanism of damping in layered and jointed welded structures. Anno et al. [10] have established that the steel plates welded with plug joints exhibit higher damping compared to other forms of welded joints.

In the present work response surface methodology with Box–Benhken (BB) design of experiment approach has been utilized to study the mechanism of interface slip damping in layered and jointed tack welded beams with varying surface roughness. The design utilizes the initial amplitude of excitation, tack length and surface roughness at the interfaces to develop the model for the logarithmic damping decrement of the layered and jointed welded structures. Statistically designed experiments have been performed to estimate the coefficients in the mathematical model, predict the response, and check the adequacy of the model. Furthermore, the effect of the aforesaid parameters on the damping rate of such structures is investigated and discussed in detail.

II. Experimental Details

A. Mathematical models and experimental design

The logarithmic damping decrement of layered and jointed welded structures may be affected by operational control variables such as; tack length, initial amplitude of excitation and surface roughness. The relationship of the logarithmic damping decrement with respect to the first two could be estimated by a first-degree model but not with respect to the others. Hence, a second-degree model becomes expedient. A suitable second-order polynomial involving main, interaction and quadratic components have been selected based on the estimation of statistical parameters, such as; coefficient of determination (R^2), adjusted R^2, standard error of regression and analysis of variance (ANOVA). In the present work, the input variables are tack length (*L*), initial amplitude of vibration (*a*), and surface roughness (*Ra*) and the output response is the logarithmic damping decrement (δ). A second order response surface model is usually expressed as:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_i x_i^2 + \sum_{i=1}^{k} \sum_{j=1}^{k} \beta_{ij} x_i x_j + \varepsilon \qquad (1)$$

where, β_0, β_i (i = 1, 2 . . . k) and β_{ij} (i = 1, 2 . . . k, j = 1, 2 . . . k) are the unknown regression coefficients to be estimated by using the method of least squares. In this expression, ε are experimentally random errors and x_1, x_2. . . x_k are the input variables that influence the response (*y*), and *k* is the number of input factors. The method of least square is used to estimate the coefficients of the second order model. The response surface analysis is then done in terms of the fitted surface. The general form of the polynomial expression (1) could be simplified to expression (2) for the logarithmic damping decrement (δ) response as given by;

$$\begin{aligned} y = A_0 + A_1 X_L + A_2 X_a + A_3 X_{Ra} + A_{12} X_L X_a + \\ A_{23} X_a X_{Ra} + A_{13} X_L X_{Ra} + A_{11} X_L^2 + A_{22} X_a^2 + A_{33} X_{Ra}^2 \end{aligned} \qquad (2)$$

where, A_0 is the intercept, A_1, A_2, A_3 are the linear (main) effects, A_{12}, A_{23}, A_{13} are the cross product (interaction) effects, A_{11}, A_{22}, A_{33} are the quadratic effects. X_L, X_a, X_{Ra} are the coded control variables corresponding to the tack length (*L*), initial amplitude of excitation *(a)* and surface roughness (*Ra*) respectively. The transforming equations for each coded control variable are given as:

$$X_L = \frac{L-30}{10}, X_a = \frac{a-0.2}{0.1}, X_{Ra} = \frac{Ra-1.47}{0.55} \qquad (3)$$

TABLE I
IMPORTANT FACTORS AND THEIR LEVELS

Factor	Notation	Unit	Levels					
			uncoded			coded		
Tack length	*L*	mm	20	30	40	-1	0	1
Amplitude	*a*	mm	0.1	0.2	0.3	-1	0	1
Surface roughness	*Ra*	µm	0.92	1.47	2.02	-1	0	1

Hence, three orthogonal coded factor levels -1, 0, -1 with tack length *L* = 20, 30, 40 mm coded as X_L = -1, 0, 1; initial amplitude of excitation *a* = 0.1, 0.2, 0.3 mm coded as X_a = -1, 0, 1; surface roughness *Ra* = 0.92, 1.47, 2.02 µm coded as X_{Ra} = -1, 0, 1 respectively, has been used in this system. The important coded and uncoded factors and their levels are shown above in Table 1.

The lack of fit and the degree of significance of the model have been tested by analysis of variance (ANOVA) using the software MINITAB-14. The BB design of experiment runs with independent control variables in coded, uncoded forms and response are shown in Table 2.

TABLE II
LOGARITHMIC DAMPING DECREMENT RESPONSE FOR BB DESIGN OF EXPERIMENT

Runs	Factors			Coded Factors			Response
	L(mm)	*A*(mm)	*Ra*(µm)	X_L	X_a	X_{Ra}	δ
1	30	0.1	2.02	0	-1	1	0.00348
2	20	0.1	1.47	-1	-1	0	0.00408
3	30	0.1	0.92	0	-1	-1	0.00350
4	30	0.2	1.47	0	0	0	0.00189
5	40	0.2	2.02	1	0	1	0.00182
6	30	0.2	1.47	0	0	0	0.00191
7	20	0.2	2.02	-1	0	1	0.00226
8	20	0.2	0.92	-1	0	-1	0.00220
9	30	0.2	1.47	0	0	0	0.00193
10	30	0.3	0.92	0	1	-1	0.00130
11	40	0.3	1.47	1	1	0	0.00125
12	40	0.2	0.92	1	0	-1	0.00180
13	30	0.3	2.02	0	1	1	0.00131
14	40	0.1	1.47	1	-1	0	0.00312
15	20	0.3	1.47	-1	1	0	0.00152

B. Experimental set-up and experiments

An experimental set-up as shown in Fig. 1 has been fabricated to conduct the experiments. The specimens are prepared from the stock of mild steel flats with different surface roughness by tack welding two layers of various thickness and cantilever length. The cantilever specimens are then excited transversally at the amplitudes of 0.1, 0.2, 0.3 mm at their free ends with the help of a spring arrangement. The free vibration is sensed with a vibration pick-up and the corresponding signal is fed to a digital storage oscilloscope to measure the amplitudes of the first cycle (a_1), last cycle (a_{n+1}) and the number of cycles (*n*) of the steady signal. The logarithmic damping decrement is then evaluated from the expression $\delta = \ln (a_1/a_{n+1})/n$. The structure considered in the present work is a lightly damped structure where the initiation of slip is delayed and reduced at the higher modes of vibration resulting in lower damping rate. As established by Nishiwaki et al. [4], the logarithmic damping decrement is lower at the higher modes compared to first mode. Moreover, the present analysis is based on experimental results where the effect of the higher modes is automatically accounted for in the recorded time domain curves which is further used for calculating the logarithmic damping decrement.

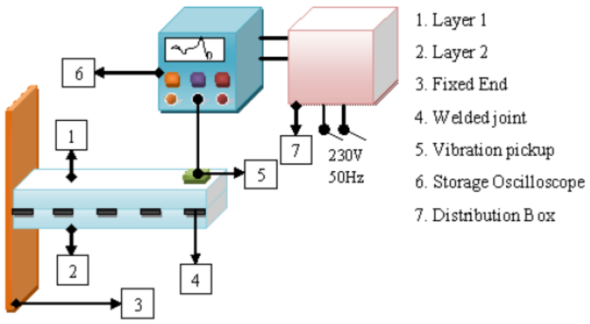

Fig. 1 Experimental set-up

III. Results and Discussion

A.Development of the response surface model for the logarithmic damping decrement (δ)

The results from the experimental runs performed as per the experimental plan are shown in Table 2. These results are used as the input data to the Minitab 14 software for further analysis following the steps outlined in Section 2. Without performing any transformation on the response, examination of the Fit Summary output have revealed that the quadratic model is statistically significant for the response and therefore it can be used for further analysis. The following equations are the final empirical models in terms of coded factors for the logarithmic damping decrement as given by;

$$\begin{aligned}\delta &= 0.00191 - 0.000259\times X_L - 0.0011\times X_a \\ &+0.000009\times X_{Ra} + 0.000103\times X_L^2 + 0.00048\times X_a^2 \\ &+0.000007\times X_{Ra}^2 + 0.000173\times X_L\times X_a \\ &-0.00001\times X_L\times X_{Ra} + 0.000007\times X_a\times X_{Ra}\end{aligned} \quad (4)$$

B. Analysis of variance (ANOVA) for logarithmic decrement

The tests for significance of the regression model, significance of individual model coefficients and lack-of-fit are to be performed to ensure the adequacy of the model. An ANOVA table is commonly used to summarize the tests performed. Table 3 shows the ANOVA table for response surface quadratic model for logarithmic damping decrement. Estimated Regression Coefficients for δ are shown in Table 4 which depicts both the significant and insignificant parameters. The value of "P" in Table 3 for model is less than 0.05 which indicates that the model is significant, which is desirable as it indicates that the terms in the model have a significant effect on the response. The value of "P" for the lack of fit in the Table 3 is more than 0.05 indicating that it is insignificant. This shows that further improvement is required in the model by eliminating the insignificant interaction terms from the model. Furthermore, the significance of each coefficient in the full model has been examined by the P-values and the results are listed in Table 4.

TABLE III
ANALYSIS OF VARIANCE FOR LOGARITHMIC DECREMENT (FULL MODEL)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	0.00001	0.000011	0.00000	294.1	0.000
Linear	3	0.00001	0.000010	0.00000	804.3	0.000
Square	3	0.00000	0.000001	0.00000	68.64	0.000
Interaction	3	0.00000	0.000000	0.00000	9.45	0.017
Residual	5	0.00000	0.000000	0.00000		
Lack-of-Fit	3	0.00000	0.000000	0.00000	16.97	0.056
Pure Error	2	0.00000	0.000000	0.00000		
Total	14	0.00001				

TABLE IV

ESTIMATED REGRESSION COEFFICIENTS FOR LOGARITHMIC DECREMENT (FULL MODEL)

Term	Coef	SE Coef	T	P
Constant	0.001910	0.000038	50.850	0.000
X_L	-0.000259	0.000023	-11.244	0.000
X_a	-0.001100	0.000023	-47.818	0.000
X_{Ra}	0.000009	0.000023	0.380	0.719
$X_L \times X_L$	0.000103	0.000034	3.031	0.029
$X_a \times X_a$	0.000480	0.000034	14.181	0.000
$X_{Ra} \times X_{Ra}$	0.000007	0.000034	0.218	0.836
$X_L \times X_a$	0.000173	0.000033	5.311	0.003
$X_L \times X_{Ra}$	-0.000010	0.000033	-0.307	0.771
$X_a \times X_{Ra}$	0.000007	0.000033	0.231	0.827

S = 0.00006506 R-Sq = 99.8% R-Sq (adj) = 99.5%

The resulting ANOVA table for the reduced quadratic model for logarithmic damping decrement has been shown in Table 5. Results from Table 5 indicate that the model is still significant. The response regression coefficients of the terms in the reduced model are shown in Table 6.

TABLE V
ANALYSIS OF VARIANCE FOR LOGARITHMIC DECREMENT (REDUCED MODEL)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	0.000011	0.000011	0.000002	892	0.000
Linear	2	0.000010	0.000010	0.000005	2033.44	0.000
Square	2	0.000001	0.000001	0.000000	173.49	0.000
Interaction	1	0.000000	0.000000	0.000000	47.53	0.000
Residual Error	9	0.000000	0.000000	0.000000		
Lack-of-Fit	3	0.000000	0.000000	0.000000	12.82	0.005
Pure Error	6	0.000000	0.000000	0.000000		
Total	14	0.000011				

TABLE VI
ESTIMATED REGRESSION COEFFICIENTS FOR LOGARITHMIC DECREMENT (REDUCED MODEL)

Term	Coef	SE Coef	T	P
Constant	0.001915	0.000024	79.530	0.000
X_L	-0.000259	0.000018	-14.597	0.000
X_a	-0.001100	0.000018	-62.079	0.000
$X_L \times X_L$	0.000103	0.000026	3.925	0.003
$X_a \times X_a$	0.000480	0.000026	18.443	0.000
$X_L \times X_a$	0.000173	0.000025	6.895	0.000

S = 0.00005011 R-Sq = 99.8% R-Sq(adj) = 99.7%

C. Surface and Contour plots for logarithmic decrement

The effects of the parameter interactions in the form of response surfaces and contour plots on the logarithmic damping decrement are shown in Figs. 2–4.

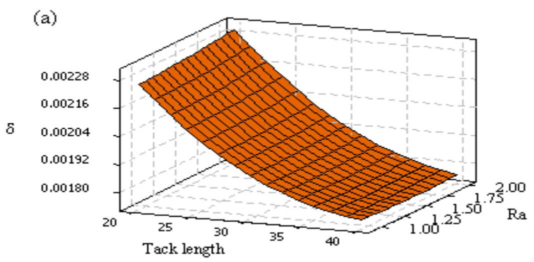

Fig. 2-a Effect of tack length and surface roughness on the logarithmic damping decrement (δ): Response surface plot

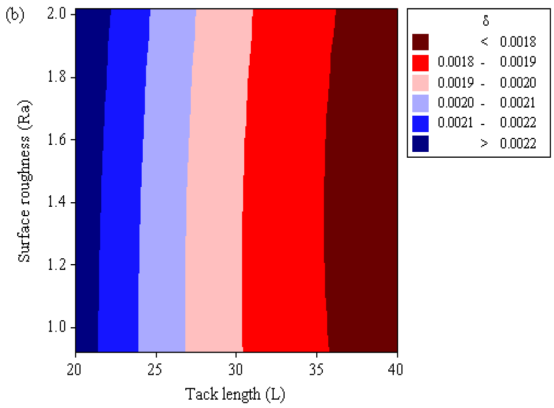

Fig. 2-b Effect of tack length and surface roughness on the logarithmic damping decrement (δ): Contour plot

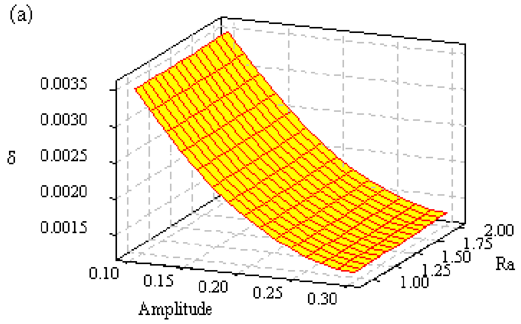

Fig. 3-a Effect of amplitude and surface roughness on the logarithmic damping decrement (δ): Response surface plot

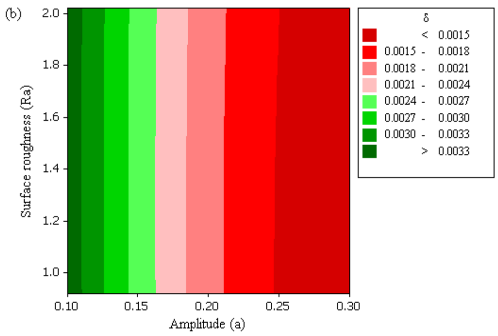

Fig. 3-b Effect of amplitude and surface roughness on the logarithmic damping decrement (δ): Contour plot

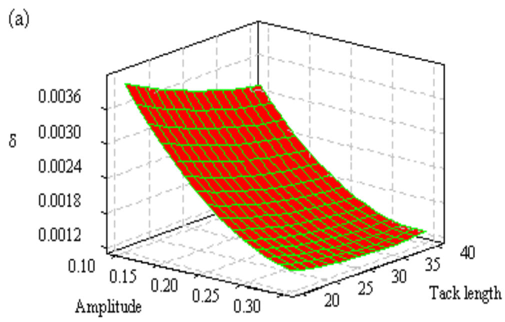

Fig. 4-a Effect of amplitude and tack length on the logarithmic damping decrement (δ): (a) Response surface plot

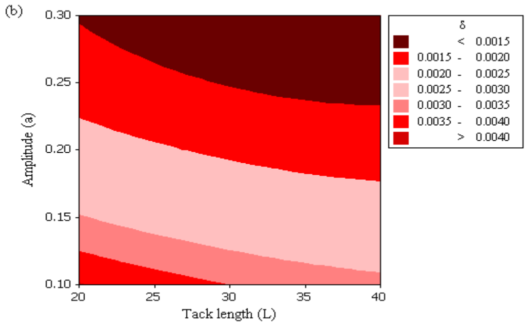

Fig. 4-b Effect of amplitude and tack length on the logarithmic damping decrement (δ): Contour plot.

The initial amplitude of excitation of free vibration is an important parameter influencing the logarithmic damping decrement of layered and jointed welded structures. The logarithmic damping decrement of such structures decreases with an increase in amplitude of excitation. This decrease is due to introduction of higher strain energy into the system compared to that of the dissipated energy due to interface friction.

The logarithmic damping decrement increases with the decrease in the length of the tack. The frequency of vibration depends on the stiffness and mass. With the decrease in the length of the tack weld, the static bending stiffness ($k = 3EI/l^3$) remains same but the overall mass decreases because of the less deposition of weld material. The frequency of vibration being directly proportional to the square root of the static bending stiffness and inversely proportional to the square root of the mass increases due to decrease in mass deposition in case of tack welded joints. Hence the product "$\alpha \times \mu$" is enhanced as established by [11] resulting in an increase in the logarithmic damping decrement as evident from Figs. 2-4.

D. Main effects of interaction on logarithmic decrement

The main effects plot for δ has been shown in Fig. 5. These plots are used to compare the changes in the level means to see which factors influence the response the most. The surface roughness effect line is almost parallel to the X-axis which denotes that the effect of surface roughness on δ is almost negligible. Furthermore, the slope of amplitude is more than the tack length with respect to the X-axis which shows that the effect of amplitude is more pronounced than tack length on the response as evident from Fig .5.

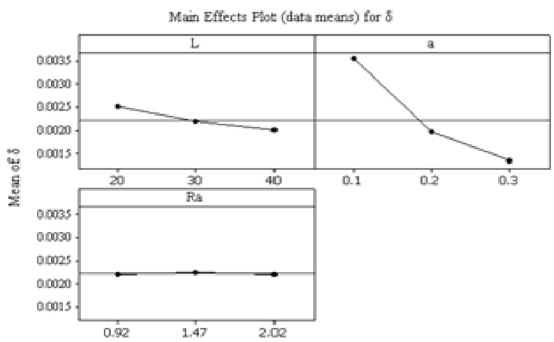

Fig. 5 Main effects plot for logarithmic decrement (δ).

E. Residual Plots for logarithmic decrement

The regression model is used for determining the residuals of each individual experimental run. The difference between the measured values and predicted values are called residuals. The residuals are calculated and ranked in ascending order. The normal probabilities of residuals for both the responses are shown in Fig. 6. The normal probability plot is used to vary the normality assumption. As shown in Fig. 6, the data are spread roughly along the straight line for δ. Hence, it is concluded that the data are normally distributed.

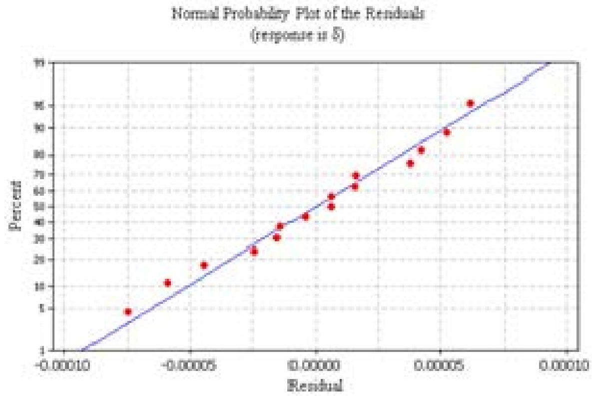

Fig. 6 Normal probability plot of the residuals

F. Validity of the model

The performance of the developed model has been tested using five experimental data which are not used in the modeling process. The results for the response "δ" predicted by the developed model in expression 5 have been used to evaluate the theoretical values of the logarithmic damping decrement and compared with the experimental ones. Furthermore, average percentage deviation between the experimental and theoretical values of logarithmic damping decrement has been calculated and presented in the Table 7. The results indicate that the model predicting the values of logarithmic damping decrement has good validity with acceptable percentage deviation of 7.56 %.

TABLE VII
COMPARISON OF THE THEORETICAL AND EXPERIMENTAL LOGARITHMIC DAMPING DECREMENT

Parameters			Logarithmic damping decrement		
L(mm)	a(mm)	Ra(µm)	Theoretical	Experimental	Deviation (%)
25	0.5	1.52	0.000959	0.00104	8.51
35	0.2	1.24	0.002018	0.00221	9.53
50	0.1	1.76	0.002758	0.00297	7.68
45	0.3	1.47	0.001028	0.00108	5.31
35	0.4	1.98	0.000856	0.00091	6.81

IV. CONCLUSION

This paper presents the findings of an experimental investigation into the effect of tack length, initial amplitude of excitation and the surface roughness on the logarithmic damping decrement of layered and jointed tack welded structures for the first mode of free vibration.

The relationship of "δ" with interaction parameters has been successfully obtained by using RSM at 95% confidence level. Furthermore, the response regression and variance analysis of the second order model for the response shows that surface roughness parameter is statistically insignificant and the logarithmic damping decrement is constant for a jointed interface of same material irrespective of the surface roughness. From the analysis of variance (ANOVA), it is concluded that the logarithmic damping decrement decreases with the increase in amplitude and tack length as evident from the surface and contour plots as shown in Fig.2. The damping of layered and jointed structures is inversely proportional to the initial amplitude of excitation as established by Nanda and Behera [5]. In these structures, the strain energy introduced into the system is more with higher amplitude of excitation compared to that of the dissipated energy, thereby decreasing the logarithmic damping decrement. The accuracy of the response surface model has been verified with five sets of other experimental data and the average percentage deviation has been found to be 7.56 %.

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