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Piyush, U.G., Sanjay G.

STATISTICAL MODELING APPROACH FOR MINIMIZING STRESSES DEVELOPED IN BOLTED RAIL JOINT

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Abstract: *The paper aims at formulating a statistical model for minimizing the Stresses developed in the bolted rail joint by the variation of different parameters like – distance between the sleepers, Speed of train, Total load on the train, Placement of the rail joint and finding out the optimum values of the parameters to minimize the stress value. An equation capable of predicting value of stress, for any given value of the parameters is formulated. A series of experimental values were obtained from ANSYS by Finite element analysis of the 3D model of rail joint prepared in SolidWorks. Verification of the prepared 3D model was done mathematically. A full 2^4 factorial experiment approach has been adopted to study the interaction among the parameters. Design-Expert® statistical package has been used and the formulated model is based on Analysis of Variance (ANOVA).*

Key words: *sleepers, ANOVA, finite element analysis, factorial experiment approach, stress*

Statistički modeliran pristup za smanjenje napona razvijenih u spoju šina. *Cilj rada je formulisanje statističkog modela za smanjenje napona razvijenih u spoju šina različitim varijantama parametara kao što su: - razdaljina između pragova, brzina voza, ukupnog opterećenja na vozu, postavljanja spojnice šine i pronalaženja optimalne vrednosti parametara kako bi se smanjila vrednost napona. Napravljena je jednačina koja može predvideti vrednost napona, za bilo koju vrednost parametara. Niz eksperimentalnih vrednosti dobijen je od ANSIS-a pomoću analize konačnih elemenata 3D modela železničkog spoja pripremljenog u SolidWorks-u. Verifikacija pripremljenog 3D modela obavljena je matematički. Za ispitivanje interakcije između parametara usvojen je potpuni četvorofaktorni plana eksperimenta. Korišćen je Design-Ekpert® statistički paket i formulisan model zasnovan je na analizi varijanse (ANOVA).*

Ključne reči: *pragovi, ANOVA, analiza konačnih elemenata, faktorski eksperimentalni pristup, napon*

1. INTODUCTION

Rail joint is a critical component of rail infrastructure. Rail joints are widely used in the rail network. It consists of two joint bars. The bolts, nuts and washers are used to tightly fastening the assembly. The increasing rate of travel on railways also applies increasing stresses to the rails and this requires improvement in the strength of the rail joints. The design and mode of attachment of the fish plates are factors of decisive importance as far as the strength of the rail joint is concerned. Attempts have been made to avoid gaps between the butting ends of the rails by welding the rails either together or to the fish plates, and to enhance the mechanical strength of the weld by reinforcement with the aid of straps welded to the foot and web of the rail. However, the weld seams connecting the straps to the rail tend in their turn to weaken the Joint as a whole, since the rail is damaged along the weld seam producing a weakening of the rail which is similar to that which would result from a grooving of the rail along the line of the weld seam. A primary condition for a good rail joint is that the means of attaching the fishplates shall have the greatest resistance or be subjected to the least specific stress. The attaching of the fish plates by means of rivets would appear to be best suited for the purpose, since rivets fit snugly against the walls of the holes in the parts to be connected together and in consequence are only subjected to shearing stress. Also the use of bolted rail joints is more common than the welded joints till date. Therefore in this study bolted rail joints are considered [1]. Stresses in the wheel and rail contact area at dynamic load modes usually occur in the elastic-plastic areas and loading this area usually leads to a breakage which is a result of low cyclic fatigue. In wheel and rail contact, plastic deformation gradually occurs [1]. Rail joints can be found worldwide in railway networks and are used either to connect rails or to isolate track sections for signaling purposes. Since they constitute a discontinuity, rail joints are a weak spot with a short service life in the track structure. Compared to other track elements, more frequent maintenance and renewal actions are needed [2,3].

Analysis of Variance, usually abbreviated ANOVA, is a method for comparing the fit of two models, one a reduced version of the other [4]. ANOVA is a type of general linear model suitable for factorial designs, in which one is interested in the main effects of, and interactions between, one or more factors [5]. It is a conceptually simple, powerful, and popular way to perform statistical testing on experiments that involve two or more groups [6]. The basic principle underlying the technique is that the total variation in the dependent variable is broken into one which is attributed to some specific causes is known as the variation between the samples and the one which attributed to chance is called the variations within the samples [7]. The one-way analysis of variance, in particular, is used to test whether or not the averages from several independent situations are significantly different from one another [8]. Data are collected for each factor/level combination and then analysed using analysis of variance (ANOVA). The ANOVA uses F-tests to examine a pre-specified set of standard effects, e.g. ‘main effects’ and ‘interactions’ [9].

2. EXPERIMENTAL WORK

2.1. Experimental Procedure

Analysis is done by equally distributing the total vertical load on each wheel and considering the loading conditions on one wheel. 3D modelling of the track model and assembly has been done in SOLIDWORKS 2015. Once the assembly was completed then the model was imported to ANSYS^{R16} to analyse the stresses. Tetrahedral mesh was applied to the model with suitable refinement of mesh sizes in required regions. Standard dimensions of track, wheel, fishplate, sleeper geometry are used [4]. The 3D model prepared in Solidworks is shown Figure 1.

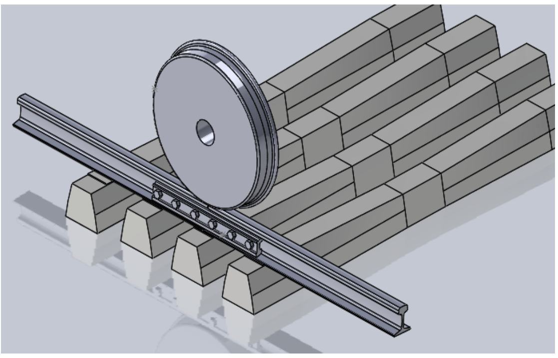

Fig. 1. 3D model of the rail joint prepared in Solidworks

2.2. Range of parameters

The four factors chosen for experiment can be controlled and play a key role in the formulation of the model. These design factors have a certain range within which they can be varied. The range of individual factors chosen are either standard values (in case of sleeper’s distance, train speed) or are calculated mathematically (total load on each wheel).

- Tare weight = 44 tonnes
- Axle weight = 7 tonnes
- Number of seats in Sleeper coach = 72
- Carrying capacity of vehicle is calculated by taking average mass of each person to be 60 Kg. Therefore, mass of people in a coach = 72*60 = 4320 Kg.

But let us also assume that each person is carrying 5 Kg of luggage with him/herself. Therefore, mass of luggage = 72*5 = 360 Kg.

Also let us assume that on each lower seat one extra person is sitting, and total compartments in a coach is 9. Hence, total extra people = 9*3 = 27 , and total mass of extra people = 27*60 = 1620 Kg.

Load on one rail wheel = Mass of [(people+luggage)+(empty coach)+(2* axle mass)/8 Kg
= [(4320+1620+360)+(40040)+(2*6370)]/8 Kg
= 7385 Kg

Therefore, weight on each wheel = 7385*9.81 = 72446.85 N

-1 in case of placement of joint, represents a suspended joint while +1 represents supported joint on the sleeper. The upper and lower limit’s actual values are shown in table 1.

Parameters	Lower limit (-1)	Upper limit (+1)
Sleeper’s distance (mm)	400	625
Train speed (Kmph)	60	120
Total load (N)	72447	107690 (for 500 extra people)
Placement of joint	Suspended joint	Supported joint

Table 1. Upper and lower limits of parameters

3. FACTORIAL APPROACH

In our design four factors are to be considered therefore the experiment design is being called a 2^4 full factorial design and it required sixteen test runs, with every possible combination of the factors amongst themselves. These sixteen observations taken in the full factorial design are shown in Table 2.

The values obtained by the Finite Element Method have been validated by hand calculations using the Strength of material’s approach [4].

Sleeper distance	Train speed	Total load	Placement of joint	Von mises Stress(MPa)
-1	1	-1	-1	64.49
1	-1	-1	-1	243.84
-1	1	1	-1	75.055
1	1	-1	-1	468
1	1	1	-1	550.49
-1	-1	1	-1	43.066
-1	-1	-1	-1	31.85
1	-1	1	-1	325.69
-1	1	-1	1	80.65
1	-1	-1	1	56.2
-1	1	1	1	96.39
1	1	-1	1	58.51
1	1	1	1	133.3
-1	-1	1	1	32.27
-1	-1	-1	1	24.4
1	-1	1	1	73.95

Table 2. Observations

4. EFFECT OF PARAMETERS ON STRESS VALUES

4.1. One factor plot

First of all it is important to know that what effects do varying each parameter separately (keeping other parameters constant) has on the model. For this purpose one factor plots are used. They also show the strength of effect each parameter is having in the model. It can be asserted from the graphs that sleeper distance (figure 2), train speed (figure 3), total load (figure 4) have positive effects, meaning an increase in any of these values will increase the stress value, while the joint placement as shown in figure 5 has a negative effect (-1 is suspended joint & +1 is supported joint).

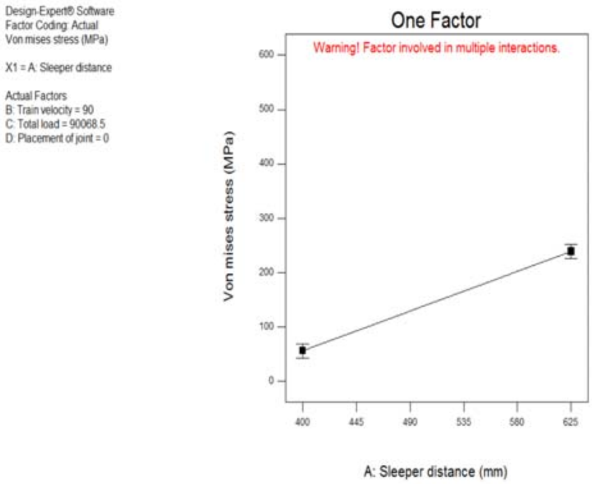

Fig. 2. One factor plot for Sleeper distance

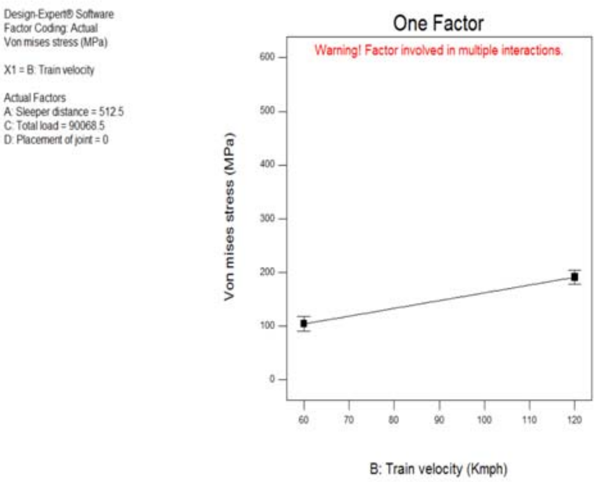

Fig. 3. One factor plot for Train velocity

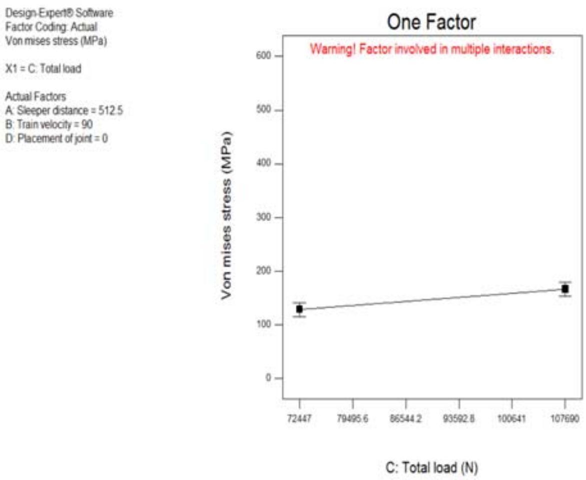

Fig. 4. One factor plot for Total load

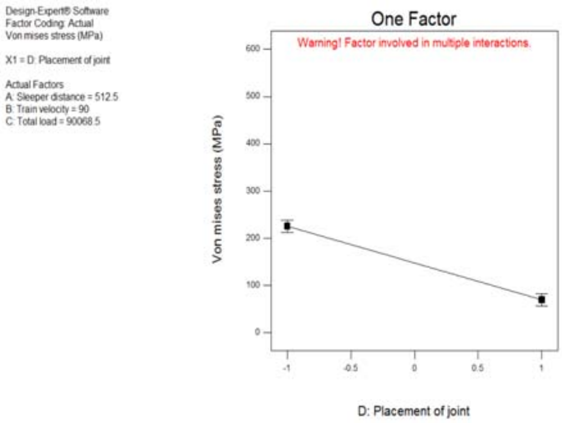

Fig. 5. One factor plot for Placement of joint

4.2. Interaction plot

Interaction plots can prove helpful to study the effect or interaction of two parameters simultaneously while keeping the other parameters constant. They tell us about whether or not there is any significant interaction between the two parameters chosen. The less parallelism the lines have, greater is the interaction between the two factors. When there is interdependence between two parameters, i.e. changing one of them has effect on the other then interaction is said to be present. Only the interaction plot of total load-train speed (figure 9) & placement of joint-total load (figure 11) show parallelism. All other interaction plots (figures 6, 7, 8, 10) do not show any parallelism between the two parameters chosen and therefore said to have an interaction between them.

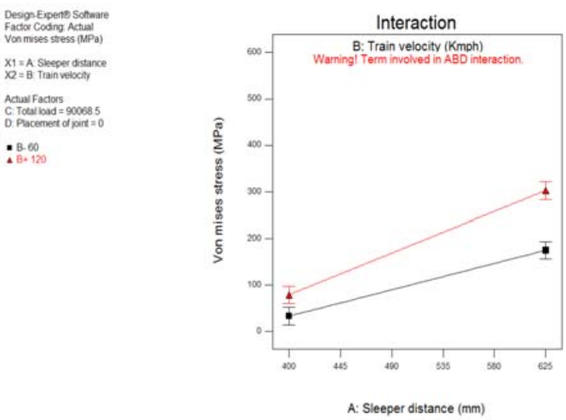

Fig. 6. Interaction plot between A and B factors

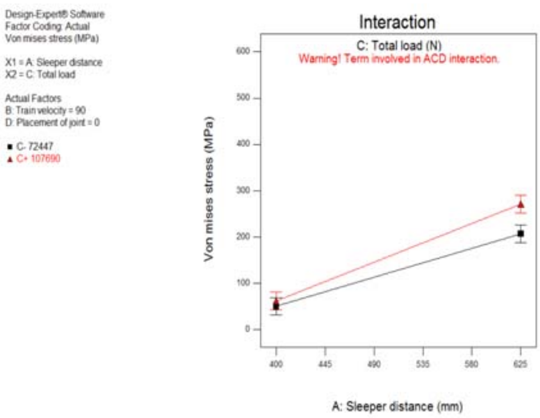

Fig. 7. Interaction plot between A and C factors

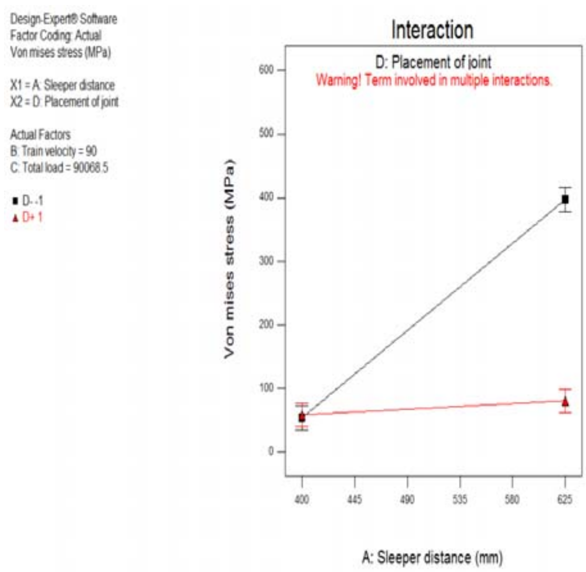

Fig. 8. Interaction plot between A and D factors

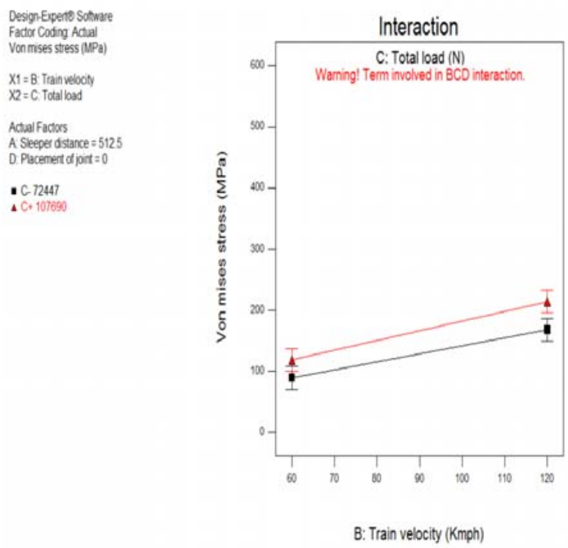

Fig. 9. Interaction plot between B and C factors

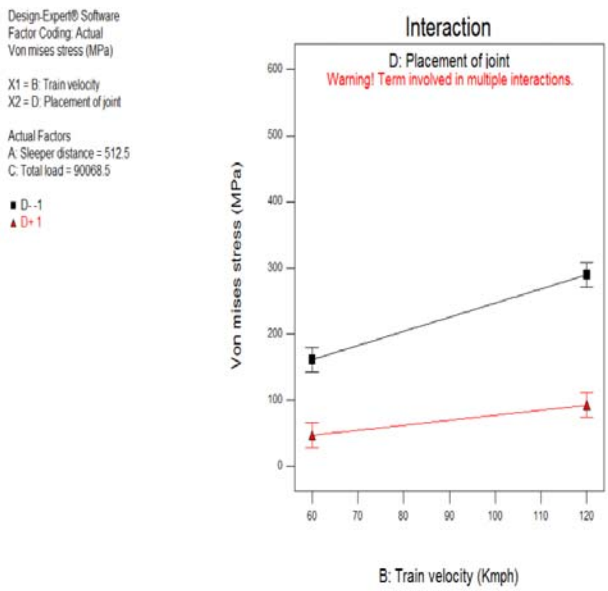

Fig. 10. Interaction plot between B and D factors

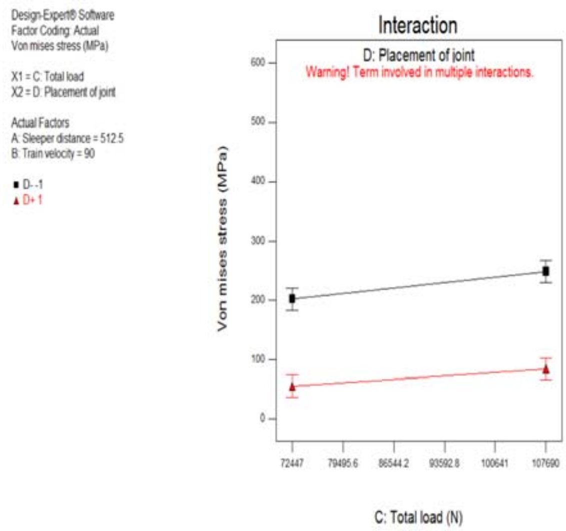

Fig.11. Interaction plot between C and D factors

4.3. Cube plot

The cube plot for Stress values shows the average stress values at those points where the parameters have their limiting values. The cube plot obtained is shown in figure 12.

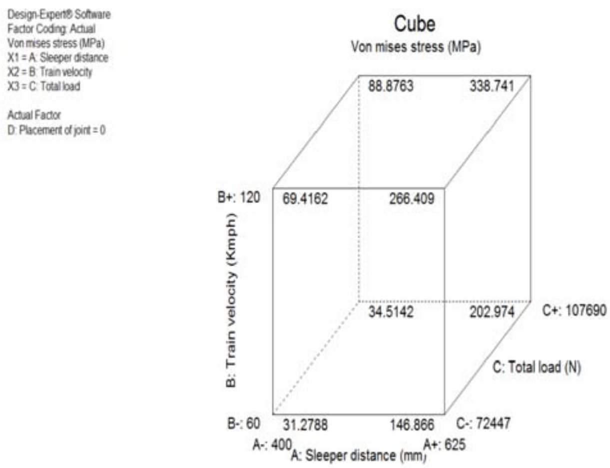

Fig. 12. Cube plot

4.4. Final equation in terms of actual factors

Von mises stress = +152.29505 – (0.33113*sleeper distance) - (2.33226*train velocity) – (3.03562E-003*placement of joint) + (6.03002E-003* Sleeper distance * Train velocity) + (6.66764E-006* Sleeper distance * Total load) + (6.66764E-006* Sleeper distance * Total load) + (0.23342* Sleeper distance * Placement of joint) + (7.67280E-006* Train velocity * Total load) + (2.82273* Train velocity * Placement of joint) + (2.50713E-004* Total load * Placement of joint) – (8.20446E-003* Sleeper distance * Train velocity * Placement of joint) – (2.32131E-006* Sleeper distance * Total load * Placement of joint) + (7.67540E-006* Train velocity * Total load * Placement of joint)

The equation formulated above can be used to predict the Stress values for given values of each parameter.

5. SIGNIFICANCE OF VARIOUS PARAMETERS

The Pareto plot and the Half Normal Plot (figure 14) helps us to determine, what is the importance and how much is the importance level of each parameter! Pareto plot shows the individual values for each of the parameter's effects. There is a t-value limit line and any factor that extends beyond this reference line is having a significant effect on the model. The t-value limit line is basically dependent on the 80-20 rule.

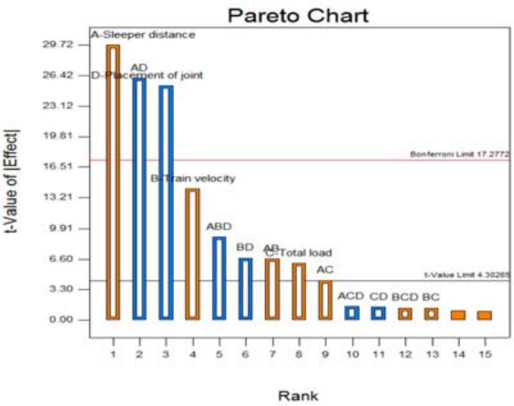

Fig. 13. Pareto chart

The effect of Sleeper distance (A) has the highest effect on the stress value followed by AD, placement of joint (D), Train speed (B), ABD, BD, AB, total load (C) as shown in figure 13.

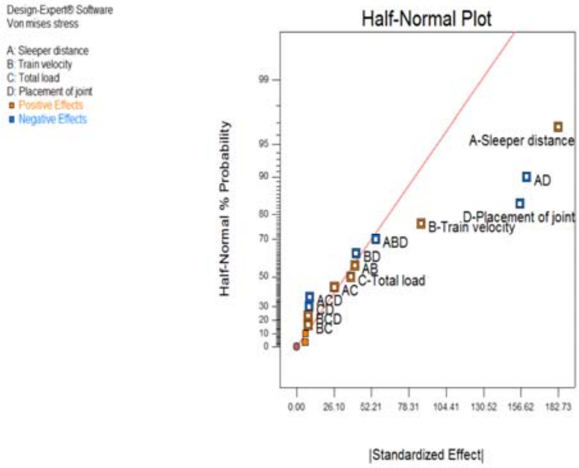

Fig. 14. Half normal plot

We use the F-statistic (or F-ratio) in the ANOVA table to make a test of the null hypothesis that all the treatment means are the same (all the αi values are zero) versus the alternative that some of the treatment means differ (some of the αi values are nonzero). When the null hypothesis is true, the F-statistic is about 1, give or take some random variation; when the alternative is true, the F-statistic tends to be bigger than 1.

Source	Sum of squares	Df	M an square	F Value	p-value Prob > F	
Model	3.997E+005	13	30742.37	203.31	0.0049	significant
A-Sleeper distance	*1.336E+005*	*1*	*1.336E+005*	*883.25*	*0.0011*	
B-Train velocity	*30242.86*	*1*	*30242.86*	*200.01*	*0.0050*	
C-Total load	*5710.48*	*1*	*5710.48*	*37.77*	*0.0255*	
D-Placement of joint	*97158.60*	*1*	*97158.60*	*642.54*	*0.0016*	
AB	*6626.81*	*1*	*6626.81*	*43.83*	*0.0221*	
AC	*2795.47*	*1*	*2795.47*	*18.49*	*0.0501*	
AD	*1.033E+005*	*1*	*1.033E+005*	*682.83*	*0.0015*	
BC	*263.24*	*1*	*263.24*	*1.74*	*0.3178*	
BD	*6870.71*	*1*	*6870.71*	*45.44*	*0.0213*	
CD	*306.00*	*1*	*306.00*	*2.02*	*0.2908*	
ABD	*12267.83*	*1*	*12267.83*	*81.13*	*0.0121*	
ACD	*338.83*	*1*	*338.83*	*2.24*	*0.2731*	
BCD	*263.42*	*1*	*263.42*	*1.74*	*0.3177*	
Residual	302.42	2	151.21			
Cor Total	4.000E+005	15				

Table 3. Analysis of variance

The Model F-value of 203.31 as shown in table 3, implies the model is significant. There is only a 0.49% chance that an F-value this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C, D, AB, AD, BD, ABD are significant model terms. Values greater than 0.1000 indicate the model terms are not significant [Design-Expert® statistical package].

Standard Deviation	12.30	R-Squared	0.9992
Mean	147.38	Adj R-Squared	0.9943
C.V. %	8.34	Predicted R-Squared	0.9516
PRESS	19354.84	Adeq Precision	45.573
-2 Log Likelihood	92.43	BIC	131.25
		AICc	540.43

Table 4. Diagnostics case statics

The "Predicted R-Squared" of 0.9516 agrees reasonably with "Adj R-Squared" of 0.9943; since the difference between them is less than 0.2. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. In this design, a ratio of 45.573 indicates an adequate signal as shown in table 4. The Predicted versus Actual values plot is used to compare the actual and predicted values and to obtain the residual as shown in figure 15.

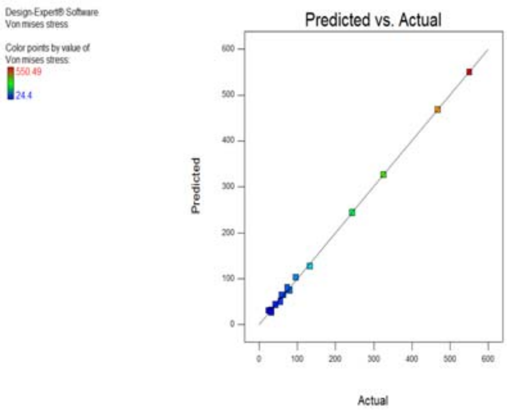

Fig. 15. Predicted vs. Actual values plot

6. MINIMIZATION AND OPTIMIZATION OF STRESS

The mathematical equation which we formulated above helps us to set the values of the four parameters in such a way that the stress value we get from this equation is minimum. We are required to set the limits of the parameters chosen, and assign a goal or condition to it; i.e. set constraints as shown in table 5. Then after running through many local solutions, the best global solution is chosen as shown in Table 6. The desirability is supposed to be close to 1, which means how close the chosen solution is to its target value.

Apart from below mentioned 21 stress values obtained, one can suitably set some different upper and lower limits of the parameters and get different combinations of the parameters altogether.

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A: Sleeper distance	is in range	400	625	1	1	3
B: Train velocity	is in range	60	120	1	1	3
C: Total load	is in range	72447	107690	1	1	3
D: Placement of joint	is in range	-1	1	1	1	3
Von mises stress	minimize	24.4	550.49	1	1	3

Table 5. Constraints

Number	Sleeper distance	Train velocity	Total load	Placement of joint	Von mises stress	Desirability	
1	400.000	60.000	107690.000	1.000	26.124	0.997	Selected
2	400.135	60.109	82823.066	1.000	29.359	0.991	
3	421.399	60.000	72496.330	1.000	32.400	0.985	
4	428.353	60.000	72448.422	1.000	33.007	0.984	
5	400.000	60.000	77040.927	-0.808	33.100	0.983	
6	434.002	60.000	72447.032	0.999	33.514	0.983	
7	439.543	61.242	72447.452	0.999	34.787	0.980	
8	460.521	60.000	72525.288	1.000	35.805	0.978	
9	459.395	60.000	74575.689	1.000	35.978	0.978	
10	471.813	60.000	73057.994	1.000	36.887	0.976	
11	491.524	60.000	72464.213	1.000	38.501	0.973	
12	495.451	60.033	72447.155	1.000	38.839	0.973	
13	455.661	60.000	106037.591	1.000	39.284	0.972	
14	512.674	60.000	72447.058	1.000	40.315	0.970	
15	526.466	60.187	72447.009	1.000	41.597	0.967	
16	524.811	65.319	72447.172	1.000	43.821	0.963	
17	574.909	60.019	72447.080	1.000	45.718	0.959	
18	551.417	66.824	72447.632	1.000	46.427	0.958	
19	574.344	60.001	72447.519	0.985	46.770	0.957	
20	592.856	60.105	72447.072	1.000	47.300	0.956	
21	592.796	60.002	72447.085	0.986	48.461	0.954	

Table 6. Solutions

7. CONCLUSION

The statistical model has been developed based on full factorial DOE and can be used for predicting and minimizing the stress value at the joint with the help of the derived equation. **Distance between the sleepers is found to be the most significant parameter** affecting the stress value followed by **placement of joint, Train speed and total load**. Mutual interaction between some of these parameters is also seen to be significant as shown in the Pareto chart. This model can be used to explain 95 percent of variability in the data.

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Authors: **Piyush U.G. Student, Sanjay Gupta Associate Professor**, Department of Manufacturing Processes and Automation Engineering, Netaji Subhas Institute of Technology, Delhi, India.
E-mail: piyush170199@gmail.com